OVERVIEW OF GROUND-LEVEL OZONE OBSERVATIONS IN ALBERTA 1986–1998

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OVERVIEW OF GROUND-LEVEL OZONE OBSERVATIONS IN ALBERTA, 1986–1998

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ACRONYMS

AAAQG	Alberta Ambient Air Quality Guideline
AOT	Accumulated exposure over a threshold concentration; a concentration weighted cumulative index calculated as a seasonal censored sum of hourly concentrations above a threshold concentration in ppb during daylight hours (0700h–2100h by default); in ppb-h
AQC	Canada-U.S. Air Quality Committee
A&WMA	Air & Waste Management Association
CASA	Clean Air Strategic Alliance
CCME	Canadian Council of Ministers of the Environment
CFD	Cumulative frequency distribution – a plot of the number of observations falling in or below an interval
CL	Critical level
CWS	Canada-Wide Standard
EPA	United States Environmental Protection Agency
LOAEL	Lowest observed adverse effect level
NAAQS	National Ambient Air Quality Standard
NO	Nitric oxide
NO_2	Nitrogen dioxide
NO_X	Nitrogen oxides
NCLAN	National Crop Loss Assessment Network
O_3	Ozone
PM	Particulate matter
ppb	Parts per billion (volume basis)
SNV	Swedish environmental protection agency
SUM	A cumulative plant-response-based index of ozone air quality calculated as a seasonal (3-month) sum of all 24-hour ozone concentrations
VOC	Volatile organic compounds
W126	A form of concentration-weighted cumulative index that uses a sigmoidal weighting function on hourly ozone concentrations to retain mid- and lower-level values

SUMMARY

This report presents an analysis of ozone data from Alberta air monitoring stations and compares observed data to current and proposed standards. As was found in previous studies, average ground-level ozone concentrations in Alberta are higher in rural areas than in city centres. While rural stations have higher average ozone concentrations, urban stations generally have higher peak ozone levels and more exceedances of the current 1-hour ambient ozone guideline (82 ppb). The high average ozone concentrations in rural areas appear to be mainly a result of downward mixing of upper tropospheric ozone, whereas discrete maximums in urban or industrial areas can be attributed to photochemistry. Most 1-hour exceedances take place in the spring and summer months during the afternoon or early evening.

The Canadian Council of Ministers of the Environment is considering a new ozone standard of 65 ppb based on a 3-year, 8-hour average. The only urban station that could have difficulty meeting the proposed 8-hour ozone standard is Edmonton Northwest. Ozone levels observed in Alberta are lower than in the U.S. The 3-year, 80-ppb standard set by the U.S. Environmental Protection Agency was not reached at Alberta stations during the period investigated.

Data are smoothed by 8-hour averaging, which may be advantageous for removing data noise in some cases. On the other hand, 1-hour concentrations can be used to pinpoint discrete maximums. Most 1-hour ozone episodes in Alberta are attributable to photochemistry in urban areas where precursors are abundant. In rural areas, however, 1-hour episodes appear to be mainly a result of downward transport of natural ozone from the upper troposphere as a result of atmospheric mixing processes. The same also appears to be true for most 8-hour episodes.

Ozone levels generally increased with temperature; however, ozone and temperature were not strongly correlated. Ozone concentrations in rural areas were found to be less dependent on temperature than in urban areas, most likely because photochemical ozone production does not dominate at rural stations where precursor concentrations are lower. Background stations, Hightower Ridge and Steeper, had the least dependence of ozone concentration on ambient temperature. It was found that the average ozone concentrations calculated for each temperature were more strongly correlated with temperature than individual ozone concentrations.

Ground-level ozone concentrations in Alberta were generally found to increase with wind speed. Few stations showed dependence of ozone on wind direction; however, the range of wind directions most commonly accompanied by greater ozone concentrations was 90-180°. Overall, ozone concentrations were not greatly influenced by surface winds, suggesting that advective transport is not a significant source of high ozone levels in Alberta.

Cumulative ozone indices such as SUM and AOT have been developed in attempts to describe how vegetation is affected by ground-level ozone. Different levels of these cumulative indices were investigated for Alberta—SUM40, SUM50, SUM60, SUM70, and AOT40. In Alberta, SUM40 values were much larger than the other indices investigated because a large number of the ozone observations were in the 40–50 ppb range. Vegetative indices were the highest at the Fort McMurray, Fort Saskatchewan, Hightower Ridge, Calgary Northwest, and Edmonton Northwest stations.

The SUM60 and AOT40 vegetative indices calculated for Alberta stations were compared to guidelines devised by various federal government working groups. The guidelines investigated, however, were set on the basis of limited data on how ozone affects crops grown in Canada. As this report shows, the high ozone concentrations observed in the vegetated (rural) areas of Alberta seem to be mainly a result of natural ozone. This being the case, regulation of anthropogenic sources or emissions would be ineffective in reducing these ozone levels.

1.0 INTRODUCTION

Ozone (O_3) in the stratosphere protects all life on the earth from harmful solar radiation. However, ozone occurring at ground level is one of the main components of smog, a noxious mixture of air pollutants seen as a haze in the air (EC, 1998b). Ground-level ozone, a reactive oxidizing agent, can be harmful to human health and vegetation and can also degrade synthetic materials. Guidelines, objectives, and standards have been set in Alberta and nation-wide to provide protection from the effects of ground-level ozone.

Air quality monitoring stations in Alberta occasionally record ground-level ozone concentrations that exceed the present guidelines. One objective of this study is to isolate these episodes, determine the meteorological conditions during and prior to the episodes, and propose causes for their occurrence.

In addition to the present ozone guidelines currently in use in Alberta and elsewhere, this report investigates a standard that is under consideration by the Canadian Council of Ministers of the Environment (CCME) for use as an indicator of human health effects. This standard takes the form of a 3-year, 8-hour average. The 8-hour averaging period, used in a past study for ozone analysis in eastern Canada (EC, 1998a), would facilitate comparison of ozone values in Canada with those in some counties in the United States that currently employ an 8-hour standard (USEPA, 1999). Clinical data appear to support the hypothesis that injury caused by ozone (i.e., respiratory system) is a response to the total delivered ozone dose over a period up to 6 to 8 hours (EC, 1997a). Clinical study results support an 8-hour averaging time on the basis that detrimental effects are normally minimal at 1 hour and increase as exposure continues (EC, 1997a). A major objective of the current study is to apply the 8-hour averaging period to Alberta and compare observations of ground-level ozone concentrations in Alberta to the proposed standard.

Two cumulative indices that have been considered for a vegetation-based ozone standard in the past are examined in this report. The SUM index is a cumulative plant-response-based index of ozone air quality calculated seasonally as the sum of all 24-hour ozone concentrations over a three month period. The AOT index (accumulated exposure over a threshold concentration) is a concentration-weighted cumulative index, which differs from the SUM index in that it is calculated as a seasonal censored sum of hourly ozone concentrations above a threshold. Different levels of these indices are investigated and compared, using ozone data from Alberta air monitoring stations.

1.1 Study Area and Data

The study area, displayed in Figure 1.1, consists of the province of Alberta and includes 17 air monitoring stations. Ground-level ozone data were obtained from the Alberta stations for the period 1986–1998. Table 1.1 lists the stations, their locations, and the periods with available data. The length of the available record varied from station to station over the study period.

The stations are classified as urban or rural, and some stations are further categorized as background, industrial, or influenced sites. Background sites are those far removed from

anthropogenic sources of ozone precursors, industrial sites are located in the vicinity of industrial emissions, and rural-influenced sites are within tens of kilometres of urban areas.

Ozone data for this study were obtained online from the CASA (Clean Air Strategic Alliance) Data Warehouse (CASA, 1999) and from the Enforcement and Monitoring Division of Alberta Environment. Data from the 17 continuous monitoring stations were obtained in the form of 1-hour averages.

1.2 Format and Terminology

This report is organized into five main sections (numbered 3.0–7.0). In sections 3.0 to 5.0, general ozone and meteorological trends are summarized and exceedances of ozone guidelines are examined. The temporal scale at which elevated ozone concentrations are found is identified and the occurrence of elevated values is compared among stations. In sections 6.0 and 7.0, more specific topics are addressed, including ozone dependence on meteorology, the proposed 8-hour ozone standard, and vegetation-based ozone indices. Conclusions are presented in section 8.0. Ozone concentrations and meteorological conditions at individual stations in Alberta are identified and stations are compared, particularly urban vs rural.

Several terms are used in this report to describe ozone. The term exceedance is used when an hourly or 8-hour ozone concentration is greater than the specified or proposed guideline value. The phrase 'ozone episode' is used to describe a period 1 hour or longer during which ozone concentrations are elevated (for example, exceedance of the 1-hour ozone guideline). Accordingly, an ozone episode is defined by an ozone exceedance, but an ozone exceedance is not necessarily an episode. Ozone concentrations are presented in units of ppb (parts per billion) of air by volume.

Figure 1.1 Alberta Air Monitoring Stations

Table 1.1 Alberta Air Monitoring Stations

Station	Type	Exact Location	Relative Location	Data Period
Beaverlodge	rural-background	55.5°N ; 119.3°W	428 km NW of Edmonton	Nov 01 97 - Dec 31 98
Calgary -Central -East -Northwest	 urban urban-industrial urban-residential	51.0°N ; 114.1°W	 611– 4 St. SW 49 Ave. and 15 St. SE 39 St. and 29 Ave. NW	Jun 01 86 - Dec 31 98
Carrot Creek	rural	53.4°N ; 115.5°W	157 km W of Edmonton	May 01 98 - Dec 31 98
Edmonton -Central -East -Northwest	 urban urban-industrial urban-residential	53.3°N ; 113.3°W	 10255 – 104 St. 105 Ave. and 17 St. 13335 – 127 St.	Jul 01 86 - Dec 31 98
Esther	rural-background	51.4°N ; 110.2°W	275 km NE of Calgary; 298 km SE of Edmonton	Jan 01 95 - Dec 31 98
Fort McMurray	urban-industrial	56.4°N ; 111.2°W	378 km NE of Edmonton	Jul 01 86 - Dec 31 98
Fort Saskatchewan	urban-industrial/ rural-influenced	53.4°N ; 113.1°W	25 km NE of Edmonton	Jul 01 86 - Dec 31 98
Hightower Ridge	rural-background	53.4°N ; 118.1°W	~300 km W of Edmonton	Jan 01 96 - Dec 31 98
Royal Park	rural	53.3°N ; 112.1°W	84 km E of Edmonton; 10 km NW of Vegreville	Jul 01 92 - May 31 97
Springbank	rural-influenced	51.1°N ; 114.4°W	20 km NNW of Calgary	Feb 23 94 - Jun 30 96
Steeper	rural	53.1°N ; 117.1°W	245 km SW of Edmonton	Dec 01 97 - Dec 31 98
Tomahawk	rural-industrial	53.2°N ; 114.5°W	88 km WSW of Edmonton	Jan 29 97 - Dec 03 98
Violet Grove	rural-industrial	53.1°N ; 115.0°W	112 km SW of Edmonton; 6 km SW of Drayton Valley	Jan 01 96 - Dec 31 98

2.0 BACKGROUND

Ozone, a colourless gas with a pungent odour, is considered a potential pollutant at ground level (Horvath et al., 1985). While most ozone occurs naturally in the stratosphere, ground-level ozone is mainly a result of human activity in populated areas. Approximately 10% of atmospheric ozone exists in the troposphere as ground-level ozone (SNV, 1993). Ozone is a *secondary* pollutant, formed from the reactions between *primary* atmospheric pollutants—nitrogen oxides (NO_X) and volatile organic compounds (VOCs). These primary pollutants (also known as precursors) are released from both anthropogenic and natural sources. In 1990, Alberta was the second greatest emitter of anthropogenic NO_X in Canada (after Ontario) and was one of the provinces that made the greatest contribution to national VOC totals (EC, 1996). For this reason, there is concern about the possible formation of photochemical smog in Alberta.

In this report, NO_X denotes the sum of NO and NO_2, which are mainly the result of combustion processes, for example, transportation, thermal electrical power plants, industrial activity, and waste incineration (EC, 1998a). Only a small percentage of NO_X is generated by natural sources such as lightning and soil microbial activity. Although most NO_X results from transportation and industrial processes in Alberta, forest fires can also contribute to NO_X concentrations in the air (Cheng et al., 1998).

VOCs are organic compounds, made of only hydrogen and carbon atoms, and are emitted by both anthropogenic and biogenic means (Moran and Morgan, 1997). The largest sources of anthropogenic VOCs are industrial and transportation processes. However, according to the 1990 Canadian Emissions Inventory of Criteria Air Contaminants, Alberta's biogenic VOC emissions (emissions from vegetation) were larger than anthropogenic emissions by a factor of more than two (EC, 1996).

Observed ground-level concentrations of ozone are the end result of many different natural and anthropogenic processes involved in the formation, transport, and destruction of ozone in the environment.

Ozone is an oxidant that is generally formed in reactions between NO_X and VOCs in the presence of sunlight. VOCs are degraded by solar radiation to form peroxy radicals, which react with nitric oxide (NO) to form the NO_2 molecules needed to form ozone (EC, 1998a). Photolysis of NO_2 by solar radiation produces an NO molecule and an oxygen (O) atom, leaving the oxygen atom to react with an oxygen molecule (O_2) to form an ozone molecule (SNV, 1993). The reactions involved in photochemical ozone production are summarized below.

NO_2 contributes to	NO_2 + sunlight	$\longrightarrow$	NO + O	ozone formation
while NO acts to	O + O_2	$\longrightarrow$	O_3	destroy ozone

Ozone destruction dominates under the following conditions: (i) high NO emissions, (ii) low solar radiation during the night, (iii) limited VOCs near NO_X sources, and (iv) limited mixing in a NO_X rich environment (Davies and Fellin, 1999). Cities often act as ozone sinks due to elevated concentrations of NO from vehicle exhaust (Angle and Sandhu, 1989). The reduction

of ozone concentrations by NO scavenging has been observed downwind of Calgary, Alberta (Leahey and Hansen, 1990). Ozone is broken down by NO according to the following reaction:

$$NO + O_3 \longrightarrow NO_2 + O_2$$

The amount of photochemical ozone produced (or destroyed) depends upon the concentrations of NO and NO_2 present, or to be more precise, the ratio of the two concentrations. The following relation (in equilibrium conditions) describes the relationship between the ratio NO_2/NO and photochemical ozone production (Leighton, 1961):

$$\frac{NO_2}{NO} = O_3 \frac{k_1}{k_3}$$

The variables k_1 and k_3 are rate constants, respectively, for the photodissociation of NO_2 (which results in ozone production) and for the depletion of O_3. According to this relation, a large NO_2/NO value suggests a peak in photochemical ozone production.

Ozone concentrations are determined by the chemistry and meteorology of the air. Ozone concentrations are elevated when photochemical ozone formation is enhanced—when solar radiation is high, precursors are in favourable ratios, and mixing and consequent dilution are inhibited. During stagnant conditions, vertical mixing is restricted and surface wind speeds are low, making it possible for pollutants, including ozone, to accumulate (Tsai et al., 1991). In addition to photochemistry, important contributors to ground-level ozone concentrations include medium- and long-range transport, mixing from the upper troposphere, and stratospheric intrusion.

Ozone may be transported from one area to another by winds. In Alberta, ozone has been transported from rural to urban locations, increasing ozone concentrations in cities (Myrick and Hunt, 1998). Ozone precursors can also be transported to less-polluted areas where ozone is then formed photochemically. Ozone concentrations may also increase as a result of mixing, which promotes the downward transport of ozone from the upper troposphere. This effect is particularly evident in rural environments, where ozone precursors are not in abundance.

Ozone injected from the stratosphere supplies the upper troposphere with a large reservoir of ozone (Singh et al., 1978). The transport of stratospheric ozone into this so-called tropospheric reservoir occurs during tropopause folding events (Davies and Schuepback, 1994). Mixing within the troposphere distributes the ozone, causing it to be gradually transported to the surface or boundary layer. Ozone-rich air from the stratosphere may also be transported directly down to the surface by large-scale turbulent motion and subsidence in a process called stratospheric intrusion (Chung and Dann, 1985). However, stratospheric intrusion events are infrequent (Ludwig et al., 1977). Ozone originating from the above two mechanisms (the tropospheric reservoir and stratospheric intrusion) is referred to in this report as natural or background ozone.

Ozone levels vary from day-to-day and from station-to-station. Rural areas represent natural or background ozone levels since they are not influenced by direct anthropogenic emissions that act to produce or destroy ozone in urban areas. Ozone in rural Alberta can most often be

attributed to transport down from the tropospheric reservoir (Singh, 1978). Rural ozone levels may also reflect photochemistry, stratospheric intrusion, or transport of ozone and its precursors from urban areas. In subsequent sections, rural and urban stations in Alberta are compared in terms of average ozone conditions, ozone exceedances, and meteorology.

Many important studies on ground-level ozone have been centred on the effects of ozone on human health and vegetation. Clinical studies have found that 6.6 hours of exposure to ozone levels of 80 ppb can result in changes in lung function, respiratory symptoms, and airway reactivity in exercising men (McDonnell et al., 1991). In addition to human health effects, ozone can degrade rubber and fabrics and is one of the most damaging air pollutants to vegetation. Studies have shown that ozone can decrease grain or seed yields, floral yields, and the numbers and weights of fruits in Alberta species (Tom, 1987). It has been suggested that the 8-hour average ozone standard provides greater protection to the public than the current 1-hour standard does in terms of ozone-induced health effects and effects on vegetation. This report does not discuss the effects of ozone on human health and vegetation in any detail, but discusses ozone formation, ambient levels, and the comparison of observations in Alberta to guidelines such as the proposed 8-hour average ozone standard and vegetative indices.

3.0 OZONE TRENDS OBSERVED IN ALBERTA

This section examines ozone trends over the period 1986–1998. The following subsections describe 1-hour and 8-hour ozone trends at air monitoring stations in Alberta, and provide comparisons between stations.

3.1 General 1-Hour Ozone Trends

Average 1-hour ozone concentrations in Alberta range from 10 ppb to 40 ppb. For comparison, the current Alberta Ambient Air Quality Guideline (AAAQG) for 1-hour ozone concentration is 82 ppb. It has been found that the lowest average ozone concentrations in Alberta occur in city centres, which has been attributed to the destruction of ground-level ozone by NO from vehicle exhaust (Davies and Fellin, 1999).

On average, the daily 1-hour ozone peak occurs at 1400–1600h, with the average daily maximum occurring at 1500h and the minimum at 0700–0800h (Figure 3.1). The daily ozone peak corresponds to the time of day with the highest temperature and deepest mixing layer, both of which enhance ozone concentrations at ground level. The highest ozone values generally occur in the spring and summer months (Figure 3.2), while minimum values are normally found in the fall or winter months when temperature, solar radiation, and mixing are lowest.

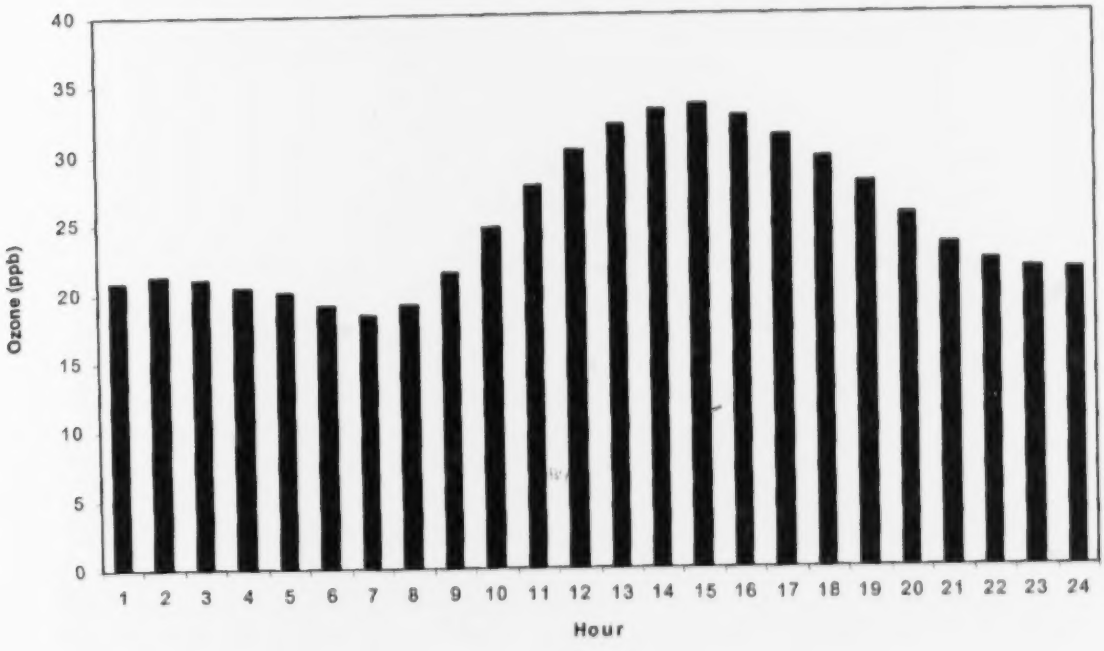

Figure 3.1 Typical hourly ozone concentrations in Alberta; an average of all stations, 1989–1998

While the discussion above applies to Alberta as a whole, 1-hour ozone values vary among the 17 air monitoring stations in Alberta, as do the lengths of ozone records. Observed ozone values depend upon various factors that combine to influence ground-level ozone levels in the area of the observation site. The trends at rural stations, for example, are different from those at urban stations. Subsection 3.1.1 discusses average conditions at each station over the respective time frame for which data were available.

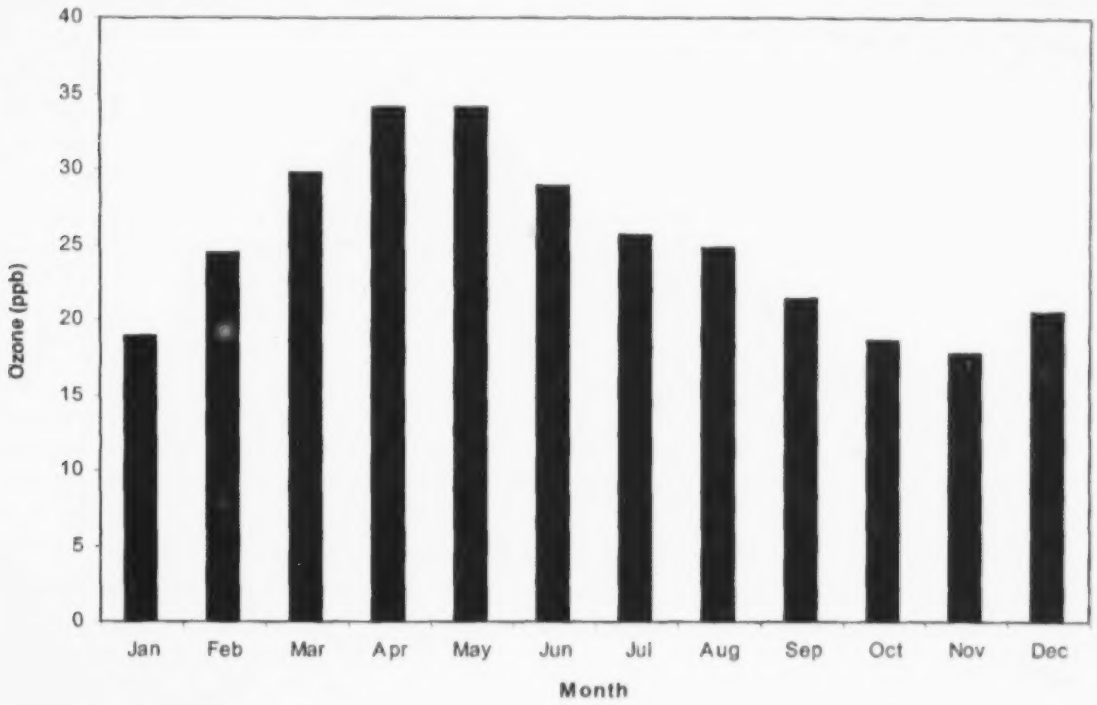

Figure 3.2 A typical year of 1-hour ozone concentrations, an average of all Alberta stations, 1989–1998

3.1.1 Average 1-Hour Ozone Concentrations at Individual Stations

A trend analysis was performed on ozone data from each Alberta station. Plots of annual 1-hour ozone variation are given in Figure 3.3, including the trends in ppb/y and regression coefficients (r) for each air monitoring station. Many stations did not have enough data points to determine whether or not there were significant ozone trends. Beaverlodge, Carrot Creek, Steeper, and Tomahawk are not included in Figure 3.3 because they had data for only one year or less.

Urban stations had very slight increasing or decreasing trends in annual average 1-hour ozone, however, there were no statistically significant trends at the 1% or 5% levels. Rural stations had increasing trends ranging from 1.0 to 3.0 ppb/y. The only Alberta station that had a statistically significant ozone trend was Royal Park, which had an upward trend of 2.7 ppb/y, significant at the 1% level. This increasing trend at Royal Park is substantiated by a drop in NO concentration from 60 ppb to 20 ppb over the 1994–1997 period.

The Alberta Environment Detailed Report for 1996 (Myrick and Hunt, 1998) reported that there were slight upward trends in annual average ozone concentration at the Edmonton Central and Calgary Central stations, most likely as a result of lower NO emissions from vehicles. To compare, data reviewed for the present study showed a very slight upward trend at Calgary Central (0.005 ppb/y), but Edmonton Central had a slight downward trend in annual average ozone (0.06 ppb/y). However, neither trend was statistically significant at the 1% or 5% levels from 1986 to 1998.

The average ozone and NO_X concentrations and meteorological conditions are summarized below for each station. The following NO_X concentration classifications are used in this report:

Low → 0–10 ppb
Moderate → 10–30 ppb
High → 30 ppb +

- **Beaverlodge (Nov 1997 – Dec 1998)**

The average 1-hour ozone concentration over the 14 months was 28 ppb. NO_X concentrations at this rural station were low; NO concentrations averaged 1 ppb and NO_2 concentrations averaged 5 ppb over the period. Winds at this station averaged 9 km/h, mainly from the south.

- **Calgary Central, East, and Northwest (Jun 1986 – Dec 1998)**

Average 1-hour ozone concentrations over this period were 14, 16, and 23 ppb at the Central, East, and Northwest stations, respectively. The lower ozone concentrations (lowest averages in the province) found at Calgary Central and East were likely due to high NO concentrations, 32 ppb and 48 ppb, respectively, and consequent ozone destruction in these areas. The average NO concentration was lower at Calgary Northwest, 12 ppb. Average NO_2 concentrations at the Central, East, and Northwest stations were 32 ppb, 27 ppb, and 18 ppb, respectively, with the highest average NO_2 concentration observed at Calgary Central. Winds in Calgary were predominantly from the south-southwest with speeds averaging 8 km/h.

- **Carrot Creek (May 1998 – Dec 1998)**

The average 1-hour ozone concentration over the 8 months was 25 ppb. This rural station observed low NO and NO_2 concentrations, averaging 1 ppb and 4 ppb, respectively. Wind speed averaged 8 km/h, primarily from the south.

- **Edmonton Central, East, and Northwest (Jul 1986 – Dec 1998)**

The average 1-hour ozone concentration was lower at the Central and Northwest stations (16 ppb and 18 ppb, respectively) than at the East station (21 ppb). This difference can be attributed to more ozone destruction by NO in central and northwest Edmonton. The average NO concentration was high at the Central and Northwest stations (33 ppb and 35 ppb, respectively) and moderate at the East station (18 ppb). Average NO_2 concentrations were 27 ppb, 18 ppb, and 22 ppb at the Central, East, and Northwest stations, respectively. Wind speed in Edmonton averaged 10–11 km/h, predominantly from the south-southwest.

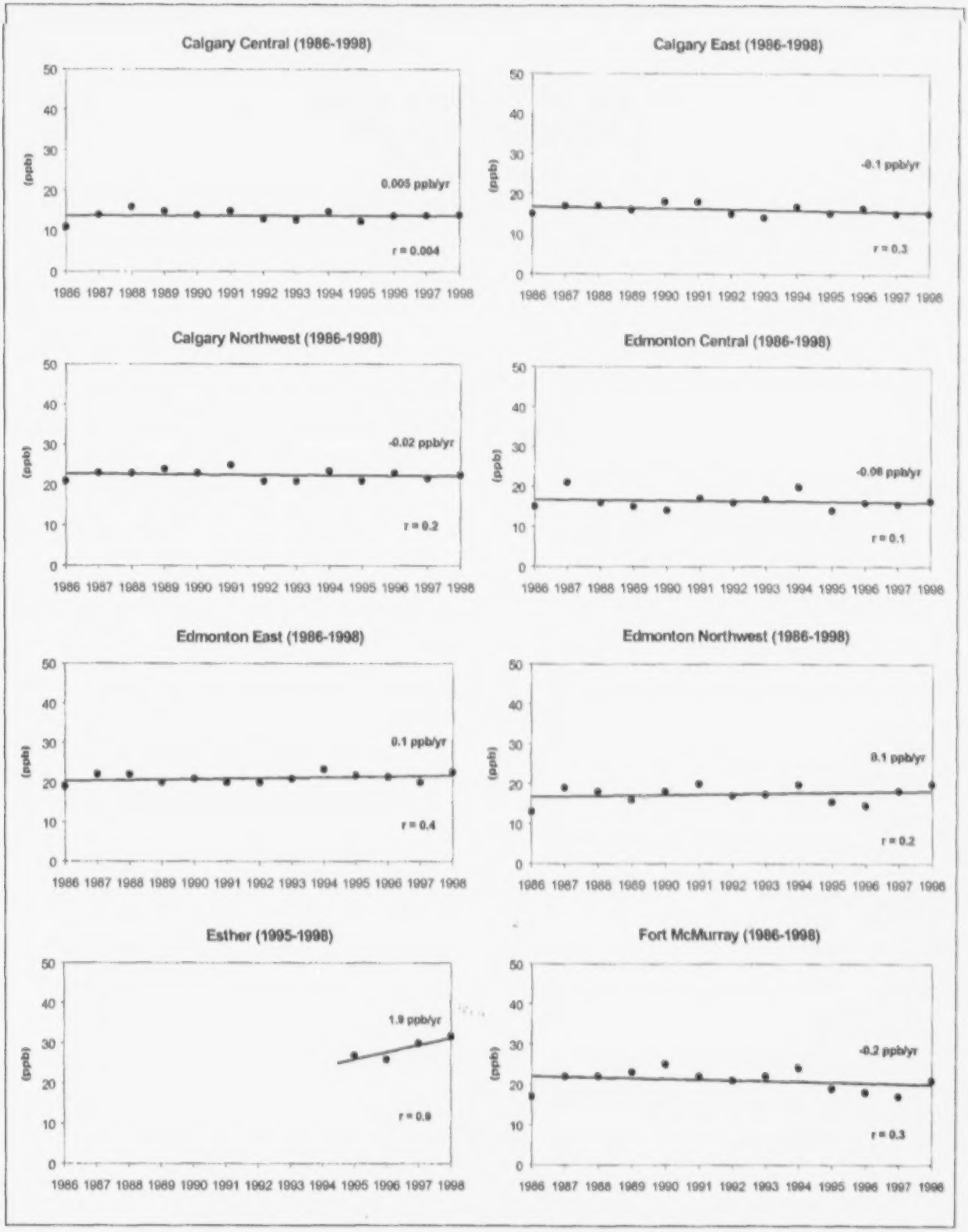

Figure 3.3 Annual 1-hour ozone trends at Alberta air monitoring stations

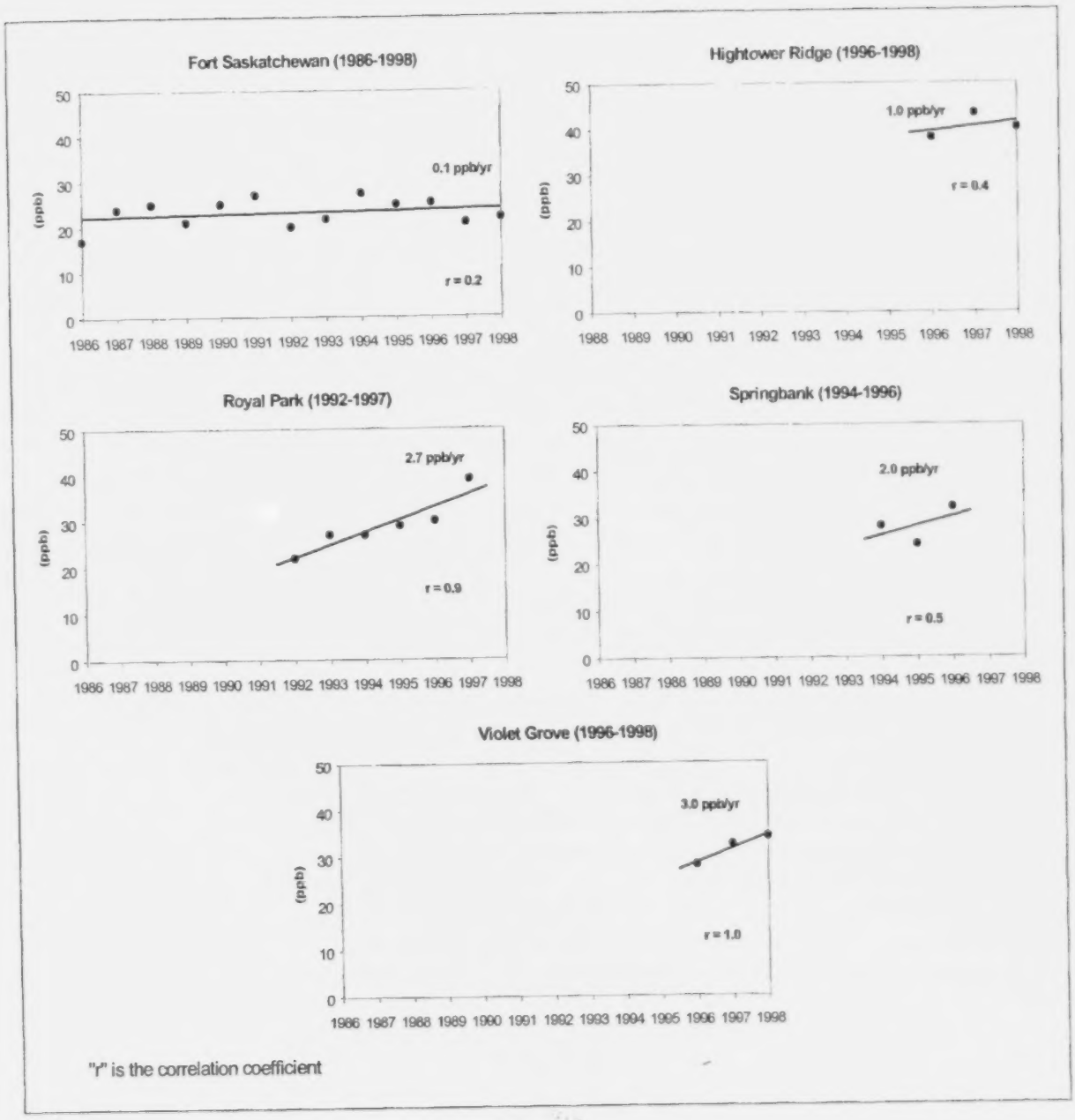

Figure 3.3 (continued)

- **Esther (Jan 1995 – Dec 1998)**

The average 1-hour ozone concentration over this period was 29 ppb. NO_X data were unavailable for this site. Wind speed averaged 15 km/h, mainly from the south-southwest.

- **Fort McMurray (Jul 1986 – Dec 1998)**

During this period the average 1-hour ozone concentration was 21 ppb. NO_X concentrations were low, averaging 9 ppb for both NO and NO_2. Average wind speed was 6 km/h, mainly from the south.

- **Fort Saskatchewan (Jul 1986 – Dec 1998)**

Over the 13 years, the average 1-hour ozone concentration was 23 ppb, which was the highest 1-hour average of all urban stations in the province. NO_X values were moderate over the period, averaging 14 ppb for NO and 13 ppb for NO_2. Average wind speed was 8 km/h, primarily from the south-southwest.

- **Hightower Ridge (Jan 1996 – Dec 1998)**

The average 1-hour ozone concentration, 40 ppb, was the highest of all stations in the province. NO_X data were not available for this rural (background) station. Average wind speed was 13 km/h, predominantly from the south-southwest.

- **Royal Park (Jul 1992 – May 1997)**

The average 1-hour ozone concentration was 31 ppb. This rural station had low NO_X concentrations, averaging 3 ppb for NO and 8 ppb for NO_2. Average wind speed was 15 km/h, mainly from the south-southwest.

- **Springbank (Feb 1994 – Jun 1996)**

The average 1-hour ozone concentration during the period was 27 ppb. NO_X data were unavailable for this site. Wind speed averaged 11 km/h, mainly from the southwest.

- **Steeper (Dec 1997 – Dec 1998)**

The average 1-hour ozone concentration over this year was 35 ppb. NO_X data were not available. Winds were mainly from the south-southeast, averaging 7 km/h.

- **Tomahawk (Jan 1997 – Dec 1998)**

Over these 3 years the average 1-hour ozone concentration was 29 ppb. NO_X concentrations were low at this station, averaging 1 ppb for NO and 4 ppb for NO_2. Winds were primarily from the south-southwest, having an average speed of 11 km/h.

- **Violet Grove (Jan 1996 – Dec 1998)**

The average 1-hour ozone concentration over this period was 32 ppb. Average NO_X concentrations at this station were low, averaging 1 ppb for NO and 3 ppb for NO_2. Winds were predominantly from the south-southwest, with an average speed of 12 km/h.

Solar radiation was measured at three stations. The averages of values measured over the 3 years were 148 W/m^2 at Hightower Ridge, 127 W/m^2 at Steeper, and 160 W/m^2 at Violet Grove.

Royal Park was the only station that had a statistically significant increase in annual average 1-hour ozone concentration. This upward trend of 2.7 ppb/y is shown in Figure 3.3.

3.1.2 Comparison of 1-Hour Ozone Concentrations at Alberta Stations

Rural stations had higher average hourly ozone concentrations than urban stations over the available data period (Figure 3.4 and Table AI.1 in Appendix I). However, unlike the average values, the peak or maximum values in cities were generally higher than the maximums at rural stations. Rural stations had lower average NO_X values, ranging from 1 to 3 ppb for NO and 3 to 8 ppb for NO_2. Urban stations, however, had NO averages ranging from 9 to 48 ppb and NO_2 averages ranging from 9 to 32 ppb.

Hightower Ridge had the highest average 1-hour ozone concentration (40 ppb) of all Alberta stations and Violet Grove had the highest maximum hourly ozone value (185 ppb). Fort Saskatchewan and Fort McMurray had the highest annual average ozone concentrations of the urban stations. In general, central urban stations had the lowest ozone values, with Calgary Central having the lowest 1-hour ozone concentration of all stations. Table 3.1 groups the stations according to ozone concentration.

Table 3.1 Range of average 1-hour ozone concentrations in Alberta

Increasing average ozone ↓

	Stations	Average 1-hour O_3	General Time Period
Urban	Calgary Central, Calgary East, Edmonton Central, and Edmonton Northwest	10 ppb – 20 ppb	1986 – 1998
	Calgary Northwest and Edmonton East	20 ppb – 25 ppb	1986 – 1998
	Fort Saskatchewan and Fort McMurray	20 ppb – 30 ppb	1986 – 1998
Rural	Beaverlodge, Esther, Springbank, and Tomahawk	25 ppb – 30 ppb	1994 – 1998
	Royal Park and Violet Grove	25 ppb – 40 ppb	1992 – 1998
	Hightower Ridge and Steeper	35 ppb – 50 ppb	1996 – 1998

At most rural stations there was less diurnal variation during the average day than at urban sites; the latter had a more pronounced ozone peak in the afternoon. A recent scientific study in Canada revealed that strong diurnal variation of ozone concentration in urban areas follows variation in NO_X concentrations (EC, 1998a). Rural stations showed higher basal ozone concentration throughout the average day, between 20 and 40 ppb, compared to urban stations, which showed a lower average base of 10–20 ppb. Figure 3.5 shows hourly ozone concentrations at a rural and an urban site in order to compare the base and peak magnitudes in the different areas.

In urban areas, the seasonal ozone peak occurred mainly in May, while in rural areas, the peak occurred slightly earlier, in March–May. Similarly, Sandhu (1999) states that natural (rural) ozone levels are expected to be at a maximum in the spring, from March through May. Some rural stations had another less-pronounced seasonal peak during the winter months (Dec and Jan).

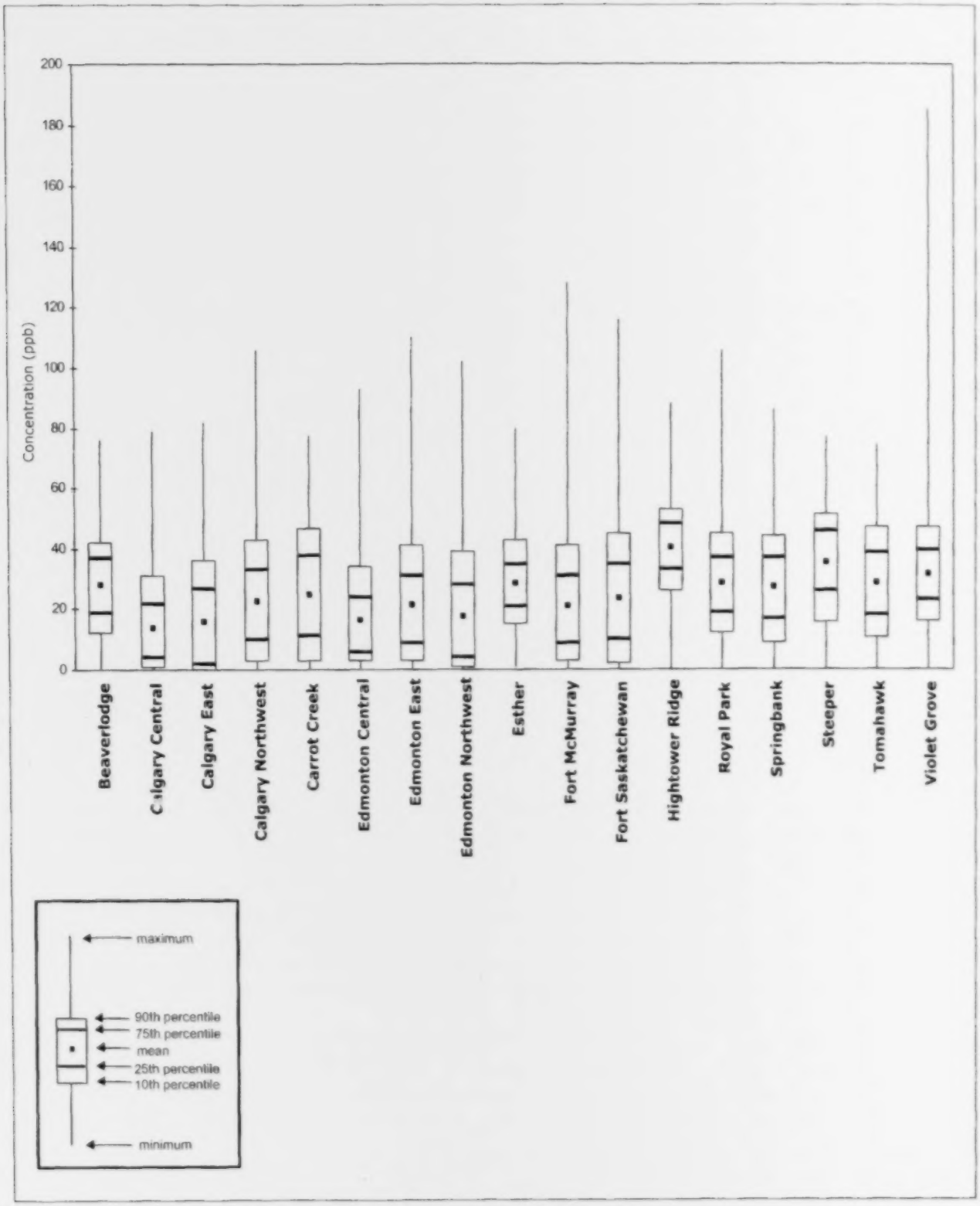

Figure 3.4 Average 1-hour ozone distribution in Alberta, 1986–1998

The lowest seasonal ozone concentrations occurred in November, December, and January at urban stations in Alberta, while minimums at rural stations occurred in September, October, and November, with a few in December. Figure 3.6 shows seasonal ozone patterns at some rural stations as well as an urban station for comparison. Over an average year, urban stations had a 1-hour ozone range of 5–35 ppb, while rural stations had a range of 20–50 ppb. The generalization can therefore be made that rural stations in Alberta exhibit higher average ozone values over a year, with less variation from month to month, compared to urban stations.

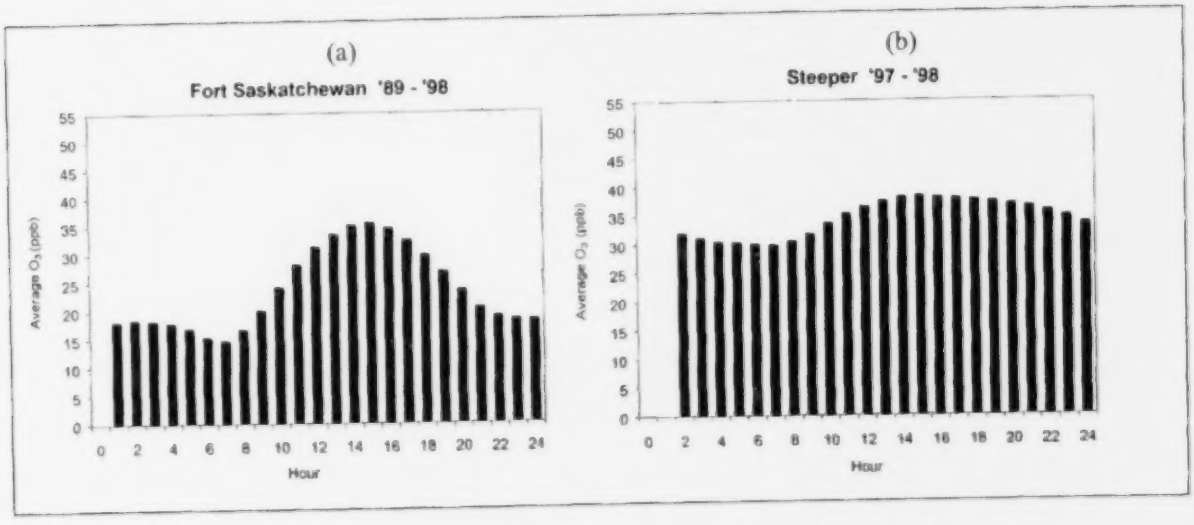

Figure 3.5 Hourly ozone concentrations at an (a) urban and (b) rural station

3.2 General 8-Hour Ozone Trends

In this study, 8-hour averages were calculated using hourly data from each station. The 8-hour average was calculated as a running average for every hour throughout the day, producing 24 values for each day. The calculation was based on end-time; therefore, 8-hour values are an average of the previous eight hourly values. The first 8-hour average in a day (0100h) is calculated as the average of the eight 1-hour values from 1700h to 2400h of the previous day. The next 8-hour value, at 0200h, is an average of the eight hourly concentrations preceding that hour, and so on. Another description of the running 8-hour average calculation is given in section 4.1.1 and is based on comparison to the proposed 8-hour Canada-Wide Standard.

Mean annual 8-hour ozone concentrations normally fall in the range of 20–30 ppb and average daily maximums range from 30 to 40 ppb. Inasmuch as 8-hour concentrations are averages of 1-hour concentrations, variations in 8-hour ozone are very similar to the 1-hour variations.

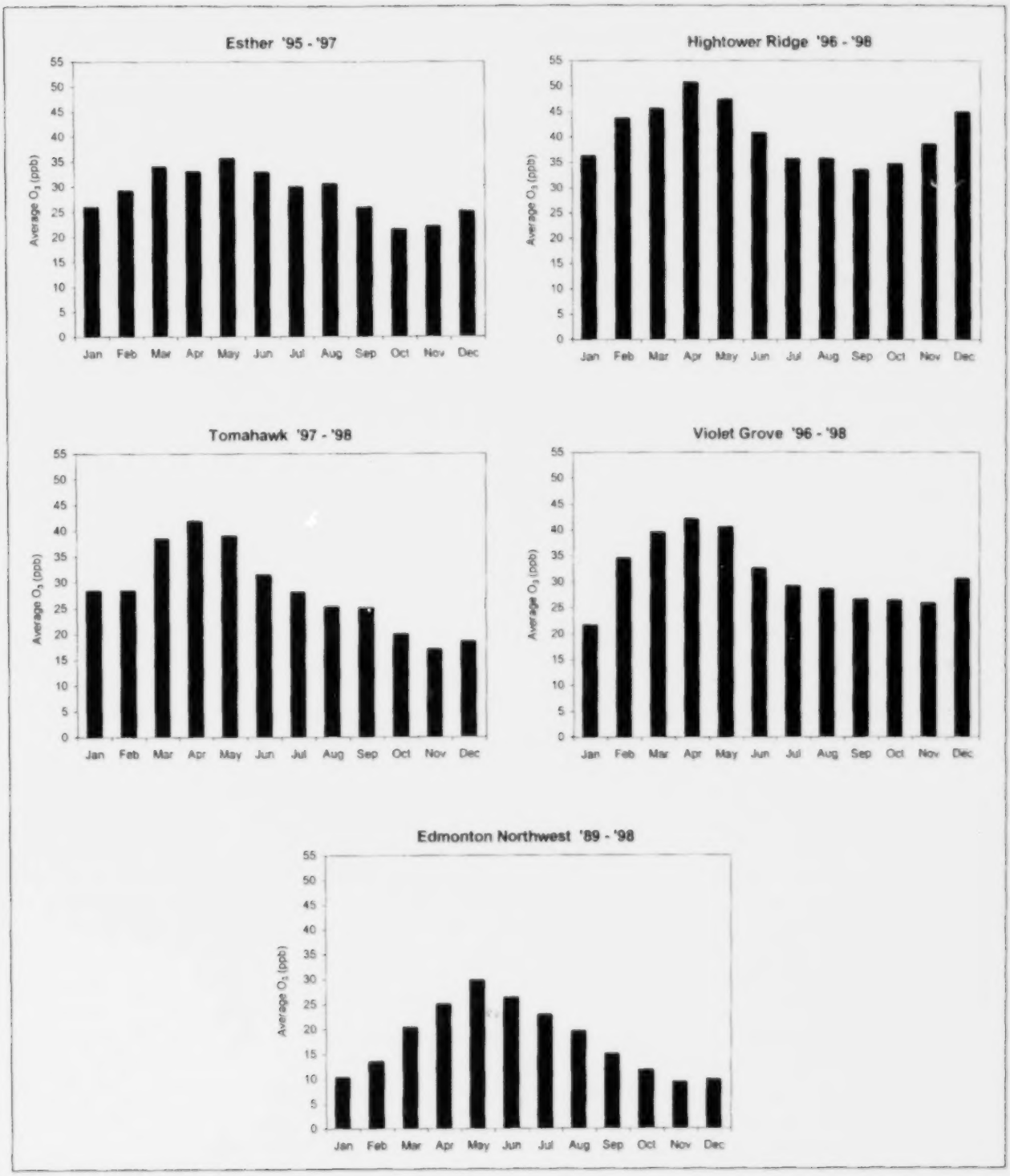

Figure 3.6 **Average seasonal 1-hour ozone concentrations at rural stations and a typical urban station**

3.2.1 *Comparison of 8-Hour Ozone Concentrations at Alberta Stations*

Like 1-hour ozone concentrations in Alberta, average 8-hour ozone values were higher in rural than in urban areas. Rural sites also had less diurnal variation of 8-hour ozone concentrations than urban sites. This trend of relatively stable 8-hour ozone concentrations through the day was most apparent at the rural stations Beaverlodge, Hightower Ridge, and Steeper (Figure 3.7).

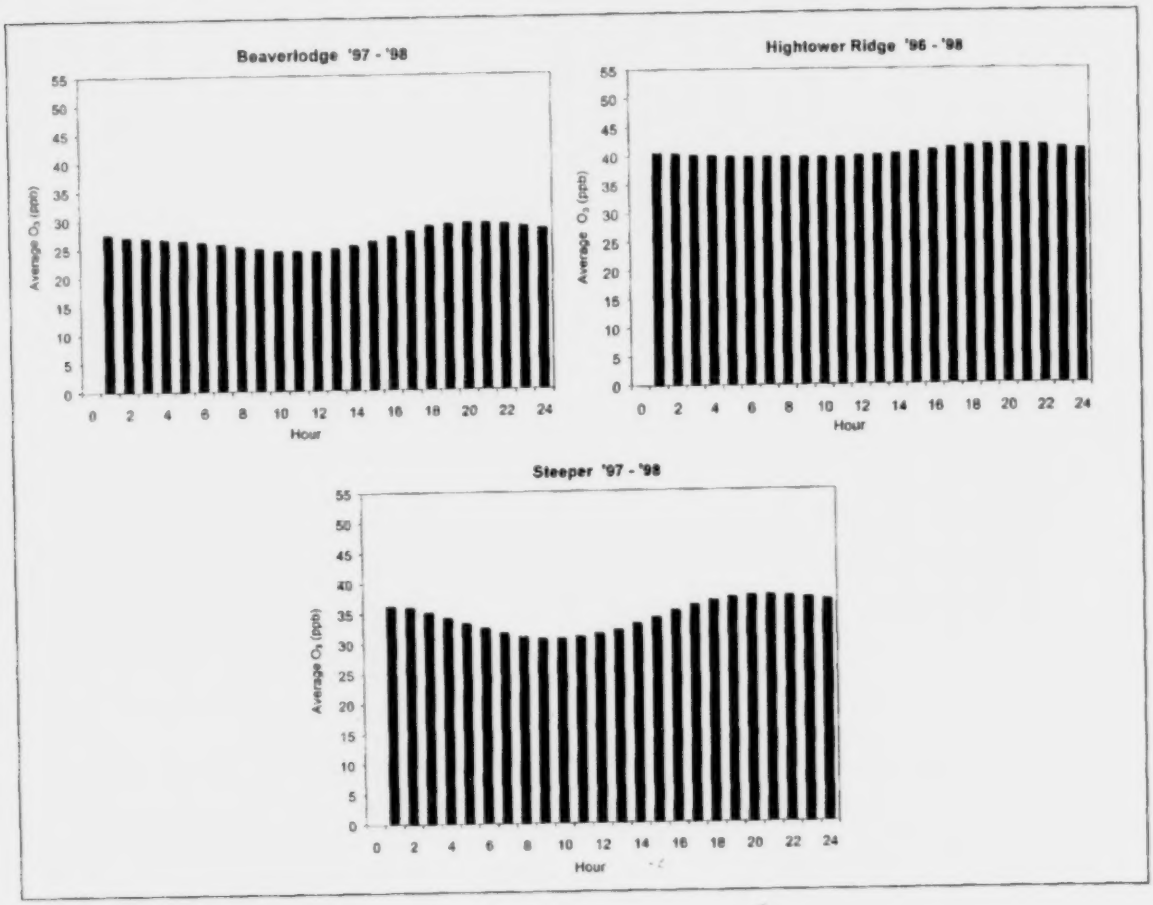

Figure 3.7 Daily 8-hour ozone concentrations at selected rural sites

The highest daily 8-hour average was found at Hightower Ridge (40 ppb) and the lowest was at Calgary Central (14 ppb). Table AI.2 and Figure AI.1 (in Appendix I) show the distribution of average 8-hour ozone concentrations between stations over their respective time frames. Violet Grove had the highest 8-hour maximum, 101 ppb, and also the highest 1-hour maximum value (refer back to Figure 3.4). Generally, 8-hour averages are higher at rural stations than urban, while 8-hour maximums have similar magnitudes in both the rural and urban settings.

Seasonal 8-hour ozone variation coincides with 1-hour trends. Urban stations showed a seasonal 8-hour peak in May and rural stations peaked in March–May. Many rural stations also had an

8-hour ozone peak in December, although it was less pronounced. The stations having the highest seasonal 8-hour ozone values were Hightower Ridge and Steeper, during the month of April. The Calgary Central and Calgary East stations had the lowest seasonal values.

3.3 Comparison of 1-Hour and 8-Hour Averaged Ozone

Generally, 1-hour and 8-hour ozone values give the same information about a station and both can be used for comparing stations or identifying stations with high ozone concentrations. However, when considering short time periods (i.e., daily or hourly), the two ozone averages differ in the information they present. Over an average day, the 8-hour ozone concentration shows less diurnal variation; the 8-hour peaks are smaller than the 1-hour peaks for the same day. The 8-hour average smoothes the ozone data, partially masking peak concentrations. However, this smoothing effect is often useful in removing noise from the data. In addition, by using end-time to represent 8-hour averages, the 8-hour ozone peaks follow average 1-hour peaks. Of course, start-time or middle-time can also be used for the calculation of running 8-hour averages.

Maximum values in the province occur at the same stations for 1-hour and 8-hour average ozone levels, but 8-hour maximums are reduced in magnitude. For example, Violet Grove had the highest maximum 1-hour value (185 ppb) on May 5, 1998 at 1800h. The highest 8-hour maximum ozone value also occurred at Violet Grove, but the value was 101 ppb on May 5, 1998 at 2300h. Therefore, in this case, the 8-hour maximum concentration is 84 ppb lower than the 1-hour maximum value. This particular ozone episode in Violet Grove is addressed further in section 5.4.3.

On average at Alberta stations, 8-hour maximums were 5–84 ppb lower than 1-hour maximums recorded during the same period. This is not surprising considering that 1-hour average concentrations are further averaged to produce an 8-hour value, causing ozone data to be smoothed considerably. It is also possible for 8-hour averages to magnify ozone episodes. For example, using end-time to calculate the 8-hour averages, if 1-hour ozone episodes occurred on two consecutive days, the maximums from the end of the first day would be included in the 8-hour averages for the following day. This raises the issue of which 8-hour averaging method to use in calculations—end-time versus start time or middle time.

4.0 PROPOSED 8-HOUR OZONE STANDARD

The following section covers the proposed 8-hour Canada-Wide Standard (CWS) for ozone and the U.S. Environmental Protection Agency (USEPA or EPA) 3-year 8-hour ozone standard. In the U.S., the 8-hour standard was established in order to provide more protection to the public against ozone-induced health effects, as well as protection from ozone-induced effects on vegetation (USEPA, 1997).

4.1 Proposed CWS for 8-Hour Ozone

The Canada-Wide Standards Development Committee for PM and Ozone has drafted recommendations for Canada-Wide Standards for ozone. A National Stakeholder Consultation Workshop was held in Calgary, May 26–May 28, 1999 to discuss standards options selected by the Development Committee and seek stakeholder comments (CWS, 1999). The proposed options were brought forward to the CCME for consideration in the fall of 1999. The CWS option for ozone, which was accepted in principle as of November 1999 (CCME, 1999), is an 8-hour average ozone target of 65 ppb based on the fourth-highest measurement annually, averaged over three consecutive years. The fourth highest 8-hour value can be viewed as adequate for both a health indicator and for shorter-term ozone management needs (CWS, 1999). The target year for compliance with the proposed ozone CWS is 2015.

More detailed information on the CWS can be found on the CCME website at:
http://www.mbnet.mb.ca/ccme/3e_priorities/3ea_harmonization/3ea2_cws/3ea2.html.

This section discusses the proposed 8-hour standard and how it affects Alberta.

4.1.1 Methodology for 3-Year 8-Hour Ozone Calculations

Hourly ozone data from each Alberta station were used to calculate 8-hour averages by the method described below. This is the methodology used to calculate the proposed 8-hour CWS (Dann, 2000).

- Calculate running 8-hour averages for every hour of every day based on end-time.
  E.g., for 0100h, the averaging period extends from 1700h of the previous day to 0100h of the following day, (this method was used in eastern Canada to calculate 8-hour averages (EC, 1998a)).
- Calculate maximum 8-hour average for each day of each year.
- Sort daily maximum 8-hour averages to obtain the fourth-highest daily maximum for a given year.
- Apply data completeness criteria (below).
- Average the fourth-highest daily maximums for three consecutive years to obtain the 3-year, 8-hour average.

Data completeness criteria for calculating running 8-hour average:
- An 8-hour average requires at least six hourly values during the 8-hour period.
- At least 50% of the hours in each month are required for it to count as a month.

- At least two months in each of the Apr–Jun and Jul–Aug quarters must be included for it to count as a year.
- At least two out of three years are required to calculate a 3-year average.

4.1.2 Three-Year 8-Hour Average in Alberta

Ozone values were calculated for Alberta air monitoring stations over an 8-hour averaging time according to the above methodology. The period chosen for calculating the 8-hour averages was 1994–1998, giving three, 3-year spans (1994–1996, 1995–1997, and 1996–1998). Table 4.1 shows the 3-year, 8-hour averages calculated for each of the stations over the 1994–1998 period. Values for Beaverlodge, Carrot Creek, and Steeper could not be calculated owing to insufficient data.

Rural stations may exceed the proposed 8-hour standard, given that they have high natural 8-hour ozone values. However, compliance with the proposed 8-hour CWS is based only on metropolitan areas with populations greater than 100 000. Currently in Alberta, this applies only to Edmonton and Calgary. It should be noted, however, that some cities in Alberta could reach the population cut-off by the proposed attainment date of 2015. The only urban station that could have difficulty meeting the proposed 8-hour ozone standard is Edmonton Northwest. Figure 4.1 compares Alberta stations to the proposed 8-hour ozone standard, which is depicted by the dotted line. The higher 3-year, 8-hour values in Alberta were observed at Fort Saskatchewan, Edmonton Northwest, Royal Park, and Violet Grove, with the highest 3-year, 8-hour average at Fort Saskatchewan: 70 ppb averaged over the 1994–1996 period.

Stations that would not be in compliance if the proposed standard were adopted as a guideline everywhere at 65 ppb are Edmonton Northwest, Fort Saskatchewan, Hightower Ridge, Royal Park, and Violet Grove. Some stations exceeded the proposed standard over the 2-year period 1997–1998, which is, however, a valid 8-hour averaging period according to the data completeness criteria (section 4.1.1). Nevertheless, a better indication of compliance would be given by adding data from 1999 to obtain a complete 3-year period.

4.2 EPA 8-Hour Ozone Standard

The USEPA is making efforts to create more stringent National Ambient Air Quality Standards (NAAQS) for ozone. The EPA proposed an 80-ppb 8-hour standard to provide increased protection for children and asthmatics, but also considered an alternative standard level of 70 ppb (USEPA, 1996). On September 16, 1997, the EPA adopted a 3-year, 8-hour standard for ozone at a level of 80 ppb, using the start hour of each 8-hour period (USEPA, 1997). The EPA 8-hour standard is calculated in the same manner as the proposed CWS, despite using the start hour instead of end-time, but the level of the EPA standard is higher (80 vs 65 ppb). The 8-hour level of 80 ppb is roughly equivalent to a 1-hour ozone concentration of 100 ppb (EC, 1997c).

Table 4.1 Three-year, 8-hour averages (ppb) in Alberta (1994–1998)

Station	Year	Dates Used	4th Highest Daily Max	3-year Average	Period
Beaverlodge	1998	Jan 01 - Dec 31	59		
Calgary Central	1998	Jan 01 - Dec 31	48		
	1997	Jan 01 - Dec 31	45	46	'97-'98
	1996	Jan 01 - Dec 31	44	46	'96-'98
	1995	Jan 01 - Dec 31	41	43	'95-'97
	1994	Jan 01 - Dec 31	50	45	'94-'96
Calgary East	1998	Jan 01 - Dec 31	52		
	1997	Jan 01 - Dec 31	52	52	'97-'98
	1996	Jan 01 - Dec 31	51	52	'96-'98
	1995	Jan 01 - Dec 31	49	51	'95-'97
	1994	Jan 01 - Dec 31	54	51	'94-'96
Calgary Northwest	1998	Jan 01 - Dec 31	62		
	1997	Jan 01 - Dec 31	58	60	'97-'98
	1996	Jan 01 - Dec 31	59	60	'96-'98
	1995	Jan 01 - Dec 31	57	58	'95-'97
	1994	Jan 01 - Dec 31	66	60	'94-'96
Carrot Creek	1998	May 01 - Dec 31	61		
Edmonton Central	1998	Jan 01 - Dec 31	55		
	1997	Jan 01 - Dec 31	47	51	'97-'98
	1996	Jan 01 - Dec 31	50	51	'96-'98
	1995	Jan 01 - Dec 31	51	49	'95-'97
	1994	Jan 01 - Dec 31	63	55	'94-'96
Edmonton East	1998	Jan 01 - Dec 31	65		
	1997	Jan 01 - Dec 31	53	59	'97-'98
	1996	Jan 01 - Dec 31	54	57	'96-'98
	1995	Jan 01 - Dec 31	62	56	'95-'97
	1994	Jan 01 - Dec 31	61	59	'94-'96
Edmonton Northwest	1998	Jan 01 - Dec 31	68		
	1997	Jan 01 - Dec 31	67	67	'97-'98
	1996	Jan 01 - Dec 31	51	62	'96-'98
	1995	Jan 01 - Dec 31	54	57	'95-'97
	1994	Jan 01 - Dec 31	63	56	'94-'96
Esther	1998	Jan 01 - Dec 31	65		
	1997	Jan 01 - Dec 31	58	61	'97-'98
	1996	Jan 01 - Dec 31	51	58	'96-'98
	1995	Jan 01 - Dec 31	56	55	'95-'97
Fort McMurray	1998	Jan 29 - Dec 31	54		
	1997	Jan 01 - Dec 23	53	54	'97-'98
	1996	Jan 01 - Dec 31	51	53	'96-'98
	1995	Jan 01 - Dec 31	59	54	'95-'97
	1994	Jan 01 - Dec 31	67	59	'94-'96
Fort Saskatchewan	1998	Jan 01 - Dec 31	65		
	1997	Jan 01 - Dec 31	58	62	'97-'98
	1996	Jan 01 - Dec 31	64	62	'96-'98
	1995	Jan 01 - Dec 31	72	65	'95-'97
	1994	Jan 01 - Dec 31	73	70	'94-'96

Table 4.1 (continued)

Station	Year	Dates Used	4th Highest Daily Max	3-year Average	Period
Hightower Ridge	1998	Jan 01 - Dec 31	67		
	1997	Jan 01 - Dec 31	67	67	'97-'98
	1996	Jan 01 - Dec 31	63	66	'96-'98
Royal Park	1996	Jan 01 - Dec 31	68		
	1995	Jan 01 - Dec 31	64	66	'95-'96
	1994	Jan 01 - Dec 31	49	60	'94-'96
Springbank	1995	Jan 01 - Dec 31	53		
	1994	Feb 23 - Dec 31	67	60	'94-'95
Steeper	1998	Jan 01 - Dec 31	69		
Tomahawk	1998	Jan 01 - Dec 31	61		
	1997	Jan 01 - Dec 31	65	63	'97-'98
Violet Grove	1998	Jan 01 - Dec 31	72		
	1997	Jan 01 - Dec 31	64	68	'97-'98
	1996	Jan 01 - Dec 31	53	63	'96-'98

In terms of the 3-year EPA standard, Figure 4.1 above shows that no Alberta stations exceeded 80 ppb over the 1994–1998 period. Although the EPA standard is based on a 3-year average of the fourth-highest daily maximum 8-hour value, the standard level of 80 ppb was also used for comparisons with individual 8-hour values.

In Alberta, there were only 16 episodes with 8-hour concentrations exceeding 80 ppb over the 1986–1998 period. Of these episodes, seven occurred at Violet Grove. However, because the Alberta stations had different data periods, Table 4.2 gives the number of 8-hour ozone concentrations exceeding 60-, 70-, and 80-ppb levels as percentages of all the 8-hour averages for a given station.

For comparison, Figure AI.2 (in Appendix I) shows the occurrences of 8-hour averages greater than 70 ppb in Alberta from 1986 to 1998. An 8-hour value of 70 ppb is roughly equivalent to the current 1-hour Canadian National Ambient Air Quality Objective of 82 ppb (EC, 1998a). There were 10 stations in Alberta with 8-hour ozone concentrations exceeding 70 ppb over the 1986–1998 period, giving a total of 291 8-hour values greater than 70 ppb. Fort Saskatchewan had 92 8-hour values exceeding 70 ppb, the most of any station. However, Violet Grove had the greatest percentage, 0.1%, of 8-hour averages exceeding 70 ppb (Table 4.2).

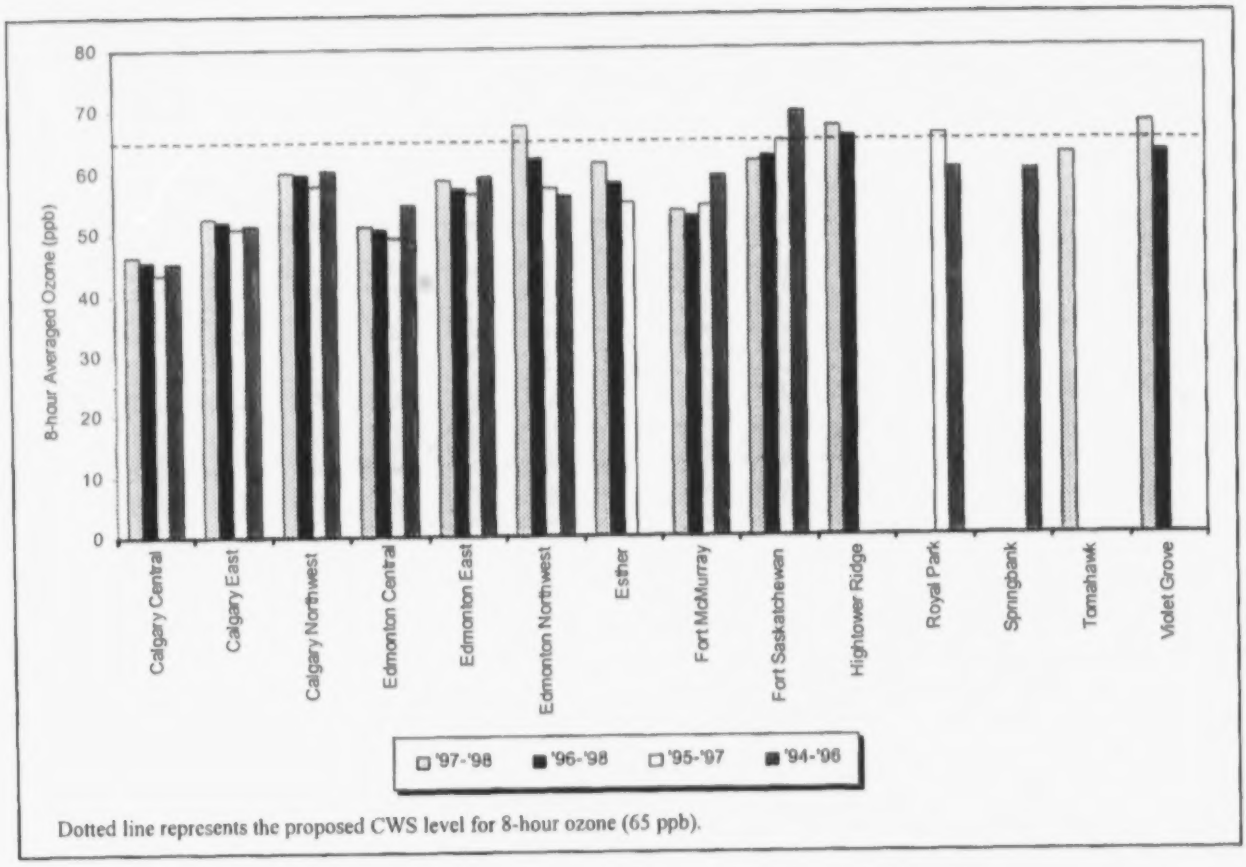

Figure 4.1 Three-year, 8-hour averages at Alberta stations (1994–1998)

For further comparison, Figure AI.3 (in Appendix I) shows the occurrences of 8-hour averages greater than 60 ppb. Throughout Alberta there were many more 8-hour averages exceeding 60 ppb than 70 ppb or 80 ppb (3741 compared to 291 and 16, respectively). Fort Saskatchewan had the most 8-hour values greater than 60 ppb, but Hightower Ridge had the greatest percentage of values exceeding 60 ppb (Table 4.2).

Alberta rarely has ozone concentrations exceeding EPA standards applicable in the United States. Rather, Alberta has ozone values much lower than the guidelines set in the U.S. As stated above, the 3-year EPA standard was not exceeded at any Alberta station over the reference period, and Alberta had only sixteen 8-hour ozone concentrations at or above 80 ppb, the current U.S. 8-hour standard. Even at an 8-hour level of 70 ppb, Alberta would have had few exceedances.

Table 4.2 Percentage of 8-hour average ozone concentrations exceeding 60, 70, and 80 ppb

Station	Percentage of 8-hour averages > 60 ppb	Percentage of 8-hour averages > 70 ppb	Percentage of 8-hour averages > 80 ppb	Years
Beaverlodge	0.04	0	0	1997 – 1998
Calgary Central	0.004	0	0	1986 – 1998
Calgary East	0.01	0	0	1986 – 1998
Calgary Northwest	0.2	0.02	0.001	1986 – 1998
Carrot Creek	0.3	0	0	1998
Edmonton Central	0.05	0.006	0	1986 – 1998
Edmonton East	0.2	0.02	0.002	1986 – 1998
Edmonton	0.3	0.02	0.001	1986 – 1998
Esther	0.2	0.01	0	1995 – 1998
Fort McMurray	0.5	0.07	0.001	1986 – 1998
Fort Saskatchewan	0.8	0.08	0.004	1986 – 1998
Hightower Ridge	1.6	0	0	1996 – 1998
Royal Park	0.4	0.03	0	1992 – 1997
Springbank	0.3	0.01	0	1994 – 1996
Steeper	1.5	0	0	1997 – 1998
Tomahawk	0.4	0	0	1997 – 1998
Violet Grove	1.0	0.1	0.03	1996 – 1998

5.0 OZONE EPISODES IN ALBERTA, 1986–1998

This section describes ozone episodes, periods when ozone concentrations exceed guidelines, and the meteorological conditions associated with these episodes. The first few subsections give the general characteristics of ozone episodes in Alberta and a comparison between stations. The last subsection (5.4) gives a detailed analysis of three different ozone episodes that occurred in Edmonton, Calgary and rural Alberta.

5.1 Current Ozone Guidelines

The AAAQG currently outlines the following ozone guideline for Alberta:

82 ppb averaged over 1 hour

In this report, a 1-hour ozone exceedance is defined as a 1-hour ozone concentration at or above 82 ppb. For comparison, an objective not used in Alberta is the Canadian National Air Quality Objective of 15 ppb for annual average ozone. All Alberta stations exceeded this annual objective over the 1986–1998 reference period, except for the central urban stations in some years.

The Canada-wide 8-hour ozone standard at a level of 65 ppb is currently being implemented by the CCME. Subsection 5.3 investigates 8-hour averaged ozone values and looks at individual exceedances of the 65-ppb concentration. Accordingly, when the term 8-hour exceedance is used in later subsections, the reference is to an 8-hour average ozone value at or above 65 ppb. The CWS level of 65 ppb is used only for comparison purposes. Compliance with the 8-hour CWS is to be based on the fourth-highest measurement annually, averaged over three consecutive years (CCME, 1999), and is not based on individual 8-hour values such as those considered in subsection 5.3.

5.2 1-Hour Ozone Episodes

Over the reference period, exceedances of the 1-hour ozone guideline generally occurred during the 1300h–1900h period. Table 5.1 shows that the most exceedances of the 1-hour guideline (21%) occurred at 1600h. Exceedances that occurred at uncharacteristic times (late night or early morning) occurred in rural areas and were most likely a result of high natural background ozone from the upper tropospheric reservoir. There were a total of 154 1-hour exceedances during the 1986–1998 reference period from all 17 air monitoring stations.

Seasonally, most exceedances of the 1-hour ozone guideline took place from May to August. Exceedances that occurred in the winter or fall months were found at rural stations such as Hightower Ridge and Violet Grove. As Table 5.1 shows, August had the most 1-hour exceedances (51 out of 154) during the 1986–1998 period, followed by July (42 of the 154 exceedances). Most of the exceedances that were recorded in May were observed at rural stations and occurred late in the evening. Exceedances of the 1-hour guideline were found to be

consecutive during the month of April, with four or five exceedances occurring in successive hours. During the summer months (June–August), however, exceedances typically occurred in isolated episodes.

Table 5.1 Hourly and monthly distributions of 1-hour ozone exceedances, 1986–1998

	Hour										Month					
	1200	1300	1400	1500	1600	1700	1800	1900	2000	Other	Apr	May	Jun	Jul	Aug	Other
No. of exceed's	3	11	22	24	33	30	15	7	2	7	13	22	23	42	51	3
% of total	2%	7%	14%	16%	21%	19%	10%	5%	1%	5%	9%	14%	15%	27%	33%	2%

Over the reference period, many Alberta stations had maximum ozone values exceeding the 1-hour guideline: Calgary East, Calgary Northwest, Edmonton Central, Edmonton East, Edmonton Northwest, Fort McMurray, Fort Saskatchewan, Hightower Ridge, Royal Park, Springbank, and Violet Grove. The number of 1-hour exceedances measured at each station is given in Figure 5.1. Figure 5.2 is a normalized plot comparing the percentage of 1-hour ozone values at or above 82 ppb over the available data period for each station.

Fort Saskatchewan had the greatest number of 1-hour ozone concentrations exceeding 82 ppb over the 1986–1998 period, as well as the greatest percentage of exceedances. Violet Grove had the second highest percentage of 1-hour exceedances in Alberta. Although rural stations had higher average ozone concentrations, the urban stations had higher peak ozone concentrations and more exceedances of the 1-hour guideline.

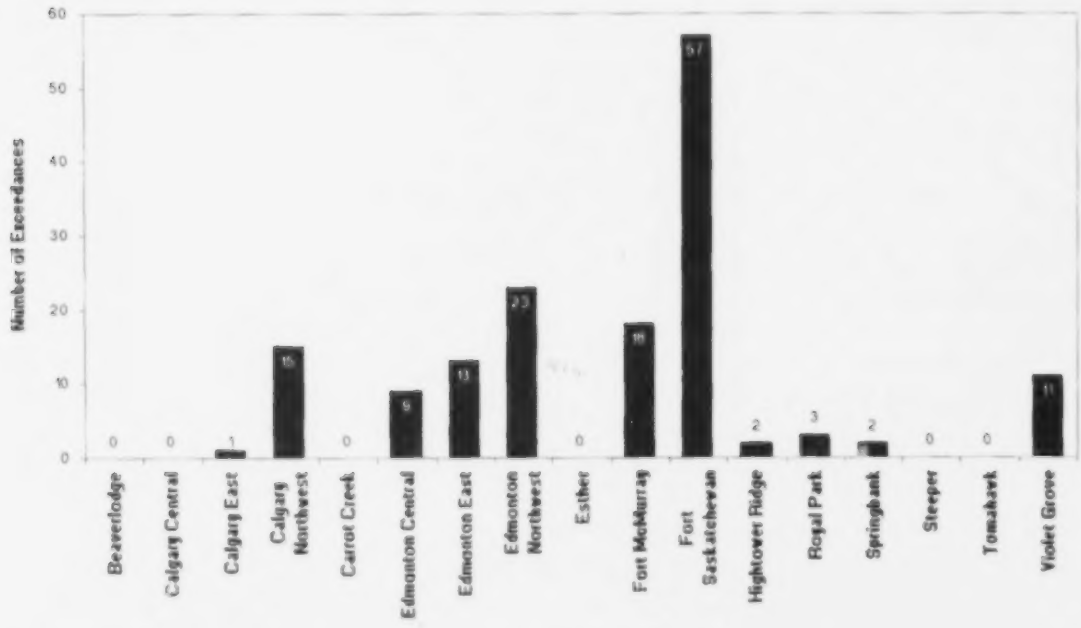

Figure 5.1 Number of 1-hour ozone exceedances at each Alberta station, 1986–1998

consecutive during the month of April, with four or five exceedances occurring in successive hours. During the summer months (June–August), however, exceedances typically occurred in isolated episodes.

Table 5.1 Hourly and monthly distributions of 1-hour ozone exceedances, 1986–1998

	Hour										Month					
	1200	1300	1400	1500	1600	1700	1800	1900	2000	Other	Apr	May	Jun	Jul	Aug	Other
No. of exceed's	3	11	22	24	33	30	15	7	2	7	13	22	23	42	51	3
% of total	2%	7%	14%	16%	21%	19%	10%	5%	1%	5%	9%	14%	15%	27%	33%	2%

Over the reference period, many Alberta stations had maximum ozone values exceeding the 1-hour guideline: Calgary East, Calgary Northwest, Edmonton Central, Edmonton East, Edmonton Northwest, Fort McMurray, Fort Saskatchewan, Hightower Ridge, Royal Park, Springbank, and Violet Grove. The number of 1-hour exceedances measured at each station is given in Figure 5.1. Figure 5.2 is a normalized plot comparing the percentage of 1-hour ozone values at or above 82 ppb over the available data period for each station.

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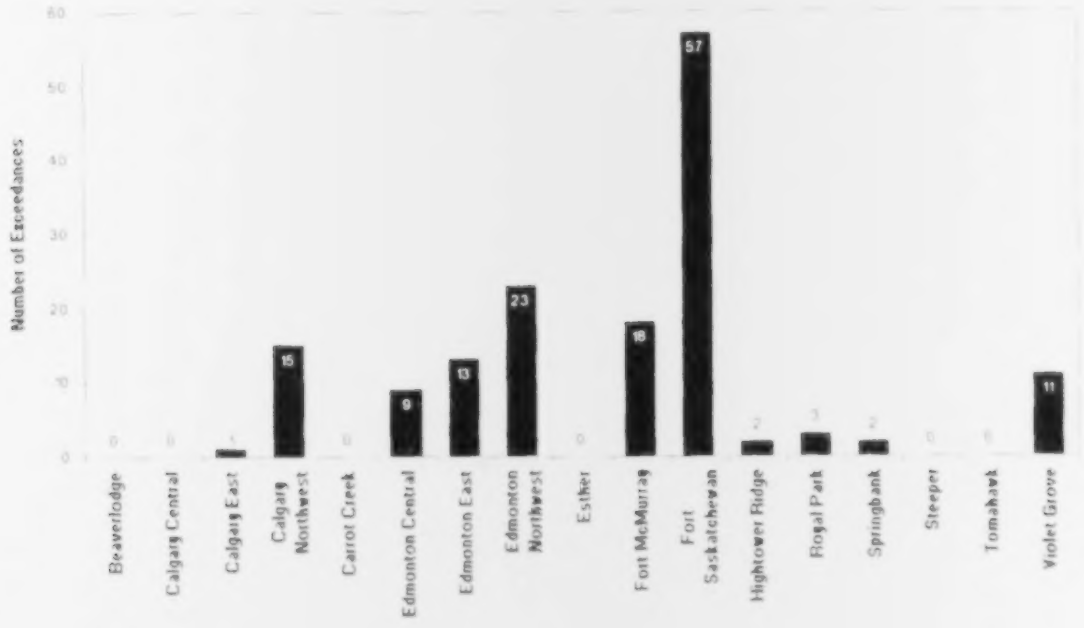

Figure 5.1 Number of 1-hour ozone exceedances at each Alberta station, 1986–1998

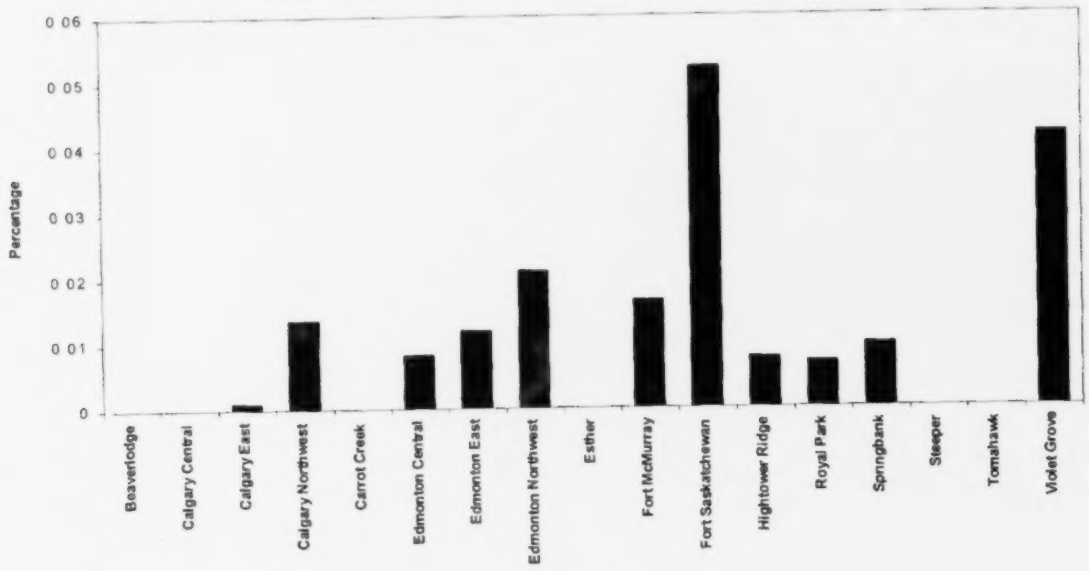

Figure 5.2 Percentage of 1-hour exceedances over the data period for each station

Peake and Fong (1990) analyzed ozone concentrations at three rural sites in southwestern Alberta: one site far removed from the Calgary urban centre and two sites located in the farmland surrounding Calgary. This study compared hourly ozone data from 1985–1987 to the Canadian air quality objective for 1-hour ozone concentration of 82 ppb. It was concluded from this 2-year study that, given Alberta's climate and meteorology, the hourly ozone guideline is more likely to be exceeded in remote areas than in cities or areas directly influenced by urban emissions (Peake and Fong, 1990). Contrary to the conclusions of Peake and Fong, the ozone data from 1986–1998 suggest that urban, not rural, stations in Alberta are more likely to exceed the current hourly ozone guideline.

5.2.1 Meteorology Associated with 1-Hour Ozone Episodes

Maximum ozone concentrations of each year were examined for Alberta air monitoring stations. Ranges for temperature, wind, and NO_X concentrations were identified for these periods in an attempt to define general conditions during periods of high ozone concentrations at Alberta air stations. Wind speeds are described in terms of the Beaufort Scale of Wind Force (given in Table AII.1 in Appendix II).

Elevated levels of ozone are generally characterized by:

- Light to moderate winds (5–20 km/h)
  Ozone episodes in Alberta that occurred during periods of *strong* winds may have been a result of transported ozone. Davies and Fellin (1999) reported that high wind speeds indicate that elevated ozone values do not originate from the vicinity. Wind direction, which varies with site location, can indicate that ozone was transported from source areas, such as large

urban centres. In addition, strong winds or large-scale turbulent motion can cause stratospheric ozone to be transported down to the troposphere (Chung and Dann, 1985).

- High temperatures (>20°C)
  Ozone episodes during periods of high temperature are most likely a result of photochemistry.
  Some ozone episodes, however, occurred during periods of *low* temperature, for example, temperatures from -10 to 5°C at the rural stations Hightower Ridge and Violet Grove. These episodes may have been the result of atmospheric mixing and downward transport of ozone from the upper troposphere or of stratospheric intrusion events.

- Low to moderate NO concentrations (0–15 ppb)
  With low levels of NO there is little ozone destruction, and photochemical ozone formation is therefore more favoured. Ozone episodes during conditions of *high* NO concentrations (>30 ppb) were found in the urban centres Edmonton Northwest and Fort McMurray. However, NO_2 concentrations were generally moderate to high during these ozone episodes, contributing to the photochemical production of ozone in the presence of VOCs and sunlight.

- High solar radiation (200–600 W/m^2)
  Solar radiation triggers the development of photochemical smog, or ground-level ozone (Moran and Morgan, 1997). Therefore, photochemical ozone formation is favoured as solar radiation increases at a polluted site. However, high solar radiation coincides with increased atmospheric mixing and does not necessarily suggest photochemical activity at rural sites, where the required precursors are normally lacking. Ozone episodes that occurred during periods of low solar radiation, for example <50 W/m^2 in Violet Grove, took place in the early spring or winter and may be indicative of ozone input from the tropospheric reservoir, stratospheric intrusion, or advective transport.

Ozone exceedances that occur during conditions that are uncharacteristic of photochemical ozone production often do so in rural areas. The conditions at Hightower Ridge in 1997 illustrate this type of occurrence. Two 1-hour ozone values of 88 ppb were measured in the months of February and November of 1997 at 2100h and 0400h, respectively. During these two periods, temperatures were below freezing, winds fluctuated from 3 to 30 km/h before the episode, and solar radiation varied from 0 to 69 W/m^2. These conditions are not typical of, and do not favour photochemical ozone production. Instead, high wind speeds prior to the exceedances could suggest that atmospheric mixing caused an input of ozone from the upper troposphere.

5.2.2 Meteorology Associated with Low Ozone Concentrations

The lowest ozone concentrations of each year were examined for all Alberta air monitoring stations. Temperature, wind, and concentrations of NO_X were studied over these periods in order to define the general meteorological conditions when ozone concentrations are low. The ranges of meteorological values recorded in Alberta during periods of low ozone concentration are described below.

Periods with low ozone concentrations in Alberta are generally characterized by:

- Calm to light winds (0–10 km/h)
  Most studies (e.g., Tsai, 1991) indicate that lighter winds result in higher ozone concentrations. This idea refers to the buildup of photochemically produced ozone under stagnant conditions. The Alberta data; however, suggest that ozone concentration in this province is more dependent on winds for the movement of natural ozone from the upper tropospheric reservoir.

- Low temperatures (<0°C)

- High NO concentrations (>100 ppb)
  High NO concentrations are commonly found in the fall or winter due to persistent temperature inversions and increased automobile emissions during these seasons (Myrick and Hunt, 1998). NO contributes to ozone destruction and subsequent removal of ozone from the air.

- Low solar radiation (0–10 W/m^2)

5.3 8-Hour Ozone Episodes

This study investigates 8-hour average exceedances of 65 ppb, and 8-hour ozone episodes are defined as periods when 8-hour averages are greater than or equal to 65 ppb. This value of 65 ppb is numerically the same as the proposed 8-hour CWS of 65 ppb, but the CWS is based on a three-year average of the fourth-highest daily maximum 8-hour average. Therefore, the level 65 ppb is only used for comparison purposes, as a reference level to examine the magnitude of 8-hour average ozone concentrations in Alberta. The CWS, however, is more complicated (refer back to section 4.1.1).

Over the 1986–1998 reference period, there were many more 8-hour episodes than 1-hour episodes. There were a total of 1283 8-hour concentrations greater than 65 ppb in Alberta compared to 154 exceedances of the 1-hour guideline (82 ppb). Because each 8-hour average covers a time span of 8 hours, each 1-hour ozone concentration in a running average scan is counted in more than one 8-hour average. As mentioned above, there were 154 1-hour exceedances in the province over the reference period. Multiplying this by eight (154x8) gives 1232, which is very close to the actual number of 8-hour exceedances (1283).

Two Alberta stations did not have 8-hour ozone concentrations at or above 65 ppb: Beaverlodge and Carrot Creek. This is most likely because of the lack of data at these stations. Table 5.2 gives the number of 8-hour concentrations exceeding 65 ppb and Figure 5.2 is a normalized plot showing the percentage of 8-hour concentrations exceeding 65 ppb based on the available hours of data at each Alberta station.

Over the entire reference period (1986–1998), Fort Saskatchewan had the most 8-hour exceedances of 65 ppb, 349, followed by Fort McMurray with 284. However, taking data period length into account for each station, the greatest percentage of 8-hour episodes was found at Steeper, where 0.6% of the 8-hour values were at or above 65 ppb. The rural stations, Steeper, Violet Grove, and Hightower Ridge had the greatest percentage of 8-hour values at or above 65 ppb in relation to the hours of data available at these stations.

Table 5.2 Occurrence of 8-hour averages at or above 65 ppb

Station	Years of data	No. of 8-h conc.'s ≥ 65 ppb	% of 8-h conc.'s ≥ 65 ppb
Beaverlodge	1997 - 1998	0	0
Calgary Central	1986 - 1998	1	0.001
Calgary East	1986 - 1998	1	0.001
Calgary Northwest	1986 - 1998	71	0.06
Carrot Creek	1998	0	0
Edmonton Central	1986 - 1998	20	0.02
Edmonton East	1986 - 1998	66	0.06
Edmonton Northwest	1986 - 1998	114	0.1
Esther	1995 - 1998	17	0.05
Fort McMurray	1986 - 1998	284	0.3
Fort Saskatchewan	1986 - 1998	349	0.3
Hightower Ridge	1996 - 1998	107	0.4
Royal Park	1992 - 1997	48	0.1
Springbank	1994 - 1996	15	0.07
Steeper	1997 - 1998	59	0.6
Tomahawk	1997 - 1998	19	0.1
Violet Grove	1996 - 1998	112	0.4
Total for Alberta		1283	

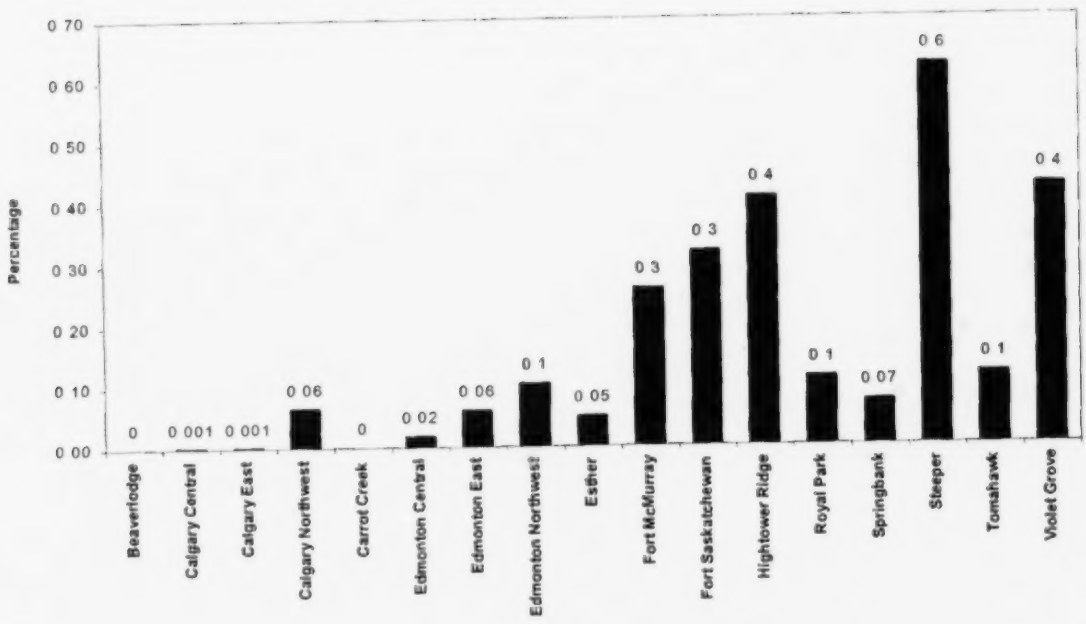

Figure 5.3 Percentage of 8-hour values at or above 65 ppb over the data period for each station

Most 8-hour episodes occurred in the spring, April and May, with almost 40% of the 8-hour concentrations exceeding 65 ppb being recorded in May (Table 5.3). There were no 8-hour average concentrations above 65 ppb during the winter months (October–December and January–February). Even though discrete maximum 1-hour events occur in the summer, average 1-hour ozone peaks in May; therefore, it is expected that the highest 8-hour values would also occur in May, when the average ozone concentration is greatest. Singh et al. (1978) attribute 1-hour ozone exceedance in the spring to the mixing down of tropospheric ozone, which is at a maximum in the spring. Therefore, since most 8-hour exceedances occur in the spring at rural stations, 8-hour exceedances are most likely a result of ozone transport from the tropospheric reservoir (natural ozone).

Table 5.3 Seasonal occurrence of 8-hour values above 65 ppb for all Alberta stations, 1986–1998

	Month											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
No. of exceed's	0	0	47	273	506	164	126	159	8	0	0	0
% of total	0%	0%	4%	21%	39%	13%	10%	12%	1%	0%	0%	0%

5.4 Trajectory Analysis

A back-trajectory analysis was performed for ozone episodes in Alberta. The selected ozone episodes are periods of one or more hours during which 1-hour ozone concentrations exceeded the AAAQG of 82 ppb. An ozone episode in an area was identified and ozone, wind, and other meteorological data were analyzed for a time period surrounding the episode. Wind data included surface winds measured at the air stations. The back-trajectory method involved using wind speed and direction to track an air parcel from the time of the ozone episode back to 14 hours prior to the episode (assuming that the air parcel travelled with the wind). On the trajectory plots in Figures 5.4h, 5.5i, and 5.6l, each symbol represents a one-hour step backward in time. Units are kilometres.

5.4.1 Calgary Airshed

The air monitoring stations chosen to represent a Calgary airshed for 1998 were Calgary Central, Calgary East, Calgary Northwest, and Esther. Although the Springbank station is closer to Calgary, Esther was used as the rural station because Springbank did not have data for 1998. Esther is located 275 km northeast of Calgary (Figure 1.1). The Calgary stations generally have low ozone concentrations and few exceedances of the 1-hour guideline (82 ppb); however, 1-hour exceedances do occasionally occur at the Calgary Northwest station. Esther did not have NO_X data, and had only incomplete meteorological data. Esther, however, was the only station with temperature data. Calgary Central had only ozone and NO_X data available for the analysis.

A trajectory analysis was performed using the surface winds measured at the air stations on July 27, 1998, prior to a 1-hour ozone exceedance. The 1-hour exceedance occurred at the Calgary Northwest station on Monday, July 27 at 1400h. There were no other 1-hour exceedances recorded in the airshed, but there were five 8-hour concentrations exceeding 65 ppb, also at Calgary Northwest. Figure 5.4a shows the hourly ozone concentrations surrounding the episode, from July 26 to 28. All four stations followed similar ozone trends, suggesting that the stations were under regional influence. Esther had the highest ozone value on July 26, but Calgary Northwest had the highest values on July 27 and 28.

The highest 1-hour ozone value on July 27, 1998 was recorded at Calgary Northwest; 84 ppb at 1400h. As shown in Figure 5.4a, the other urban stations had much lower ozone values and Esther had the lowest ozone value of the airshed during the episode. As Figure 5.4b shows, 8-hour ozone concentrations exceeded 65 ppb at Calgary Northwest from 1700 to 2100h. The average wind speed on July 27 was 7.7 km/h. The average temperature (at Esther) during this time was 21.8°C and the maximum temperature was 31.4°C. A temperature plot is not shown here since temperature data were available only for 0200h–1300h. Both ozone concentration and temperature started to increase at about 0500h and ozone concentration continued to increase with temperature until the ozone episode.

Hourly NO concentrations, Figure 5.4c, remained relatively low for all stations, despite a large peak at Calgary East at about 0100h. NO concentrations were greater at the Calgary Central and East stations, most likely as a result of the transportation and industrial processes in these areas. These two urban stations likely underwent more ozone destruction than did the Northwest

station, which would explain why they had the lower ozone values. Sandhu (1999) also reports that ozone concentrations in downtown Calgary are suppressed by nitric oxide emissions. NO_2 concentrations, shown in Figure 5.4d, were moderate to high during the episode and were lowest at Calgary Northwest. Variation in the NO_2/NO ratio is given in Figure 5.4e.

Ozone concentration was less variable at Esther than in the urban area. In addition, winds were stronger at Esther than at the urban stations (Figure 5.4f). Ozone values at Esther on July 27 probably represent natural rural (background) ozone. Winds at Esther were from the west and northeast prior to the episode (Figure 5.4g); therefore Esther was not downwind of Calgary. It is uncertain whether Esther was downwind of any other NO_X sources on July 27. Figure 5.4h shows the back-trajectories for all stations in the airshed.

At Calgary Northwest, winds were calm to light (0–10 km/h) prior to the episode and came from the northwest; they then veered around, coming from the southeast. This suggests stagnant conditions at the time of the episode. The conditions during stagnating airflow are high pressure, light winds, and recirculating airflow (Davies and Fellin, 1999). The ozone episode occurred at 1400h, following the temperature increase. NO concentration was lowest at Calgary Northwest, averaging 0–5 ppb, and providing for little ozone destruction. Since hot days with high solar radiation and relatively low wind speeds are conducive to photochemical production of ozone (Davies and Fellin, 1999), photochemistry was likely the mechanism affecting Calgary on July 27. In addition, the peaks of NO_2/NO (Figure 5.4e) are consistent with the ozone peak at Calgary Northwest, further suggesting that photochemistry was responsible for the episode at Calgary Northwest.

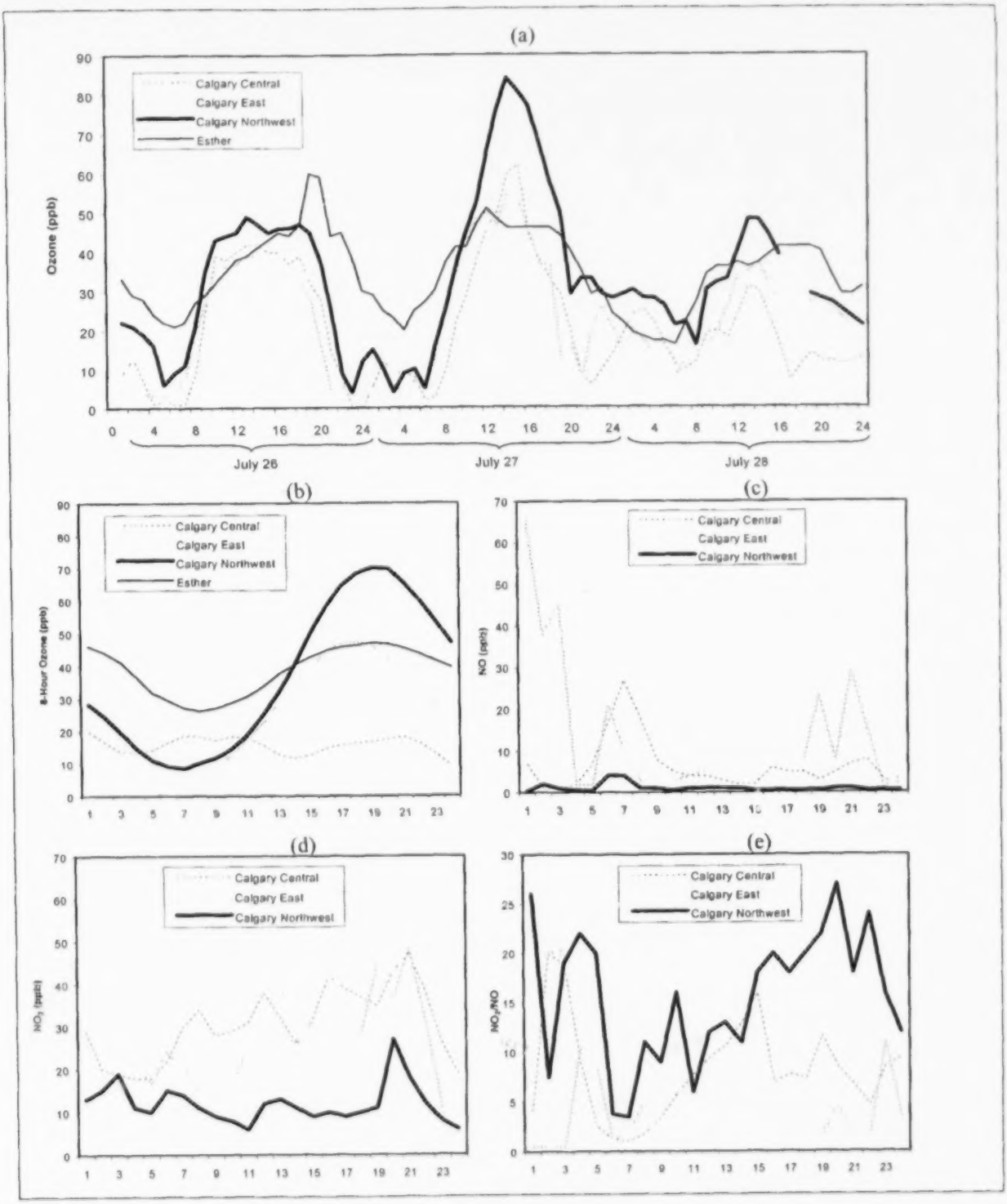

Figure 5.4 Ozone and NO_X concentrations and meteorological conditions in the Calgary area, July 1998

(a) hourly ozone (July 26, 27, and 28, 1998); (b) 8-hour ozone on July 27, 1998; (c) hourly NO concentrations on July 27, 1998; (d) hourly NO_2 concentrations on July 27, 1998; (e) NO_2/NO on July 27, 1998.

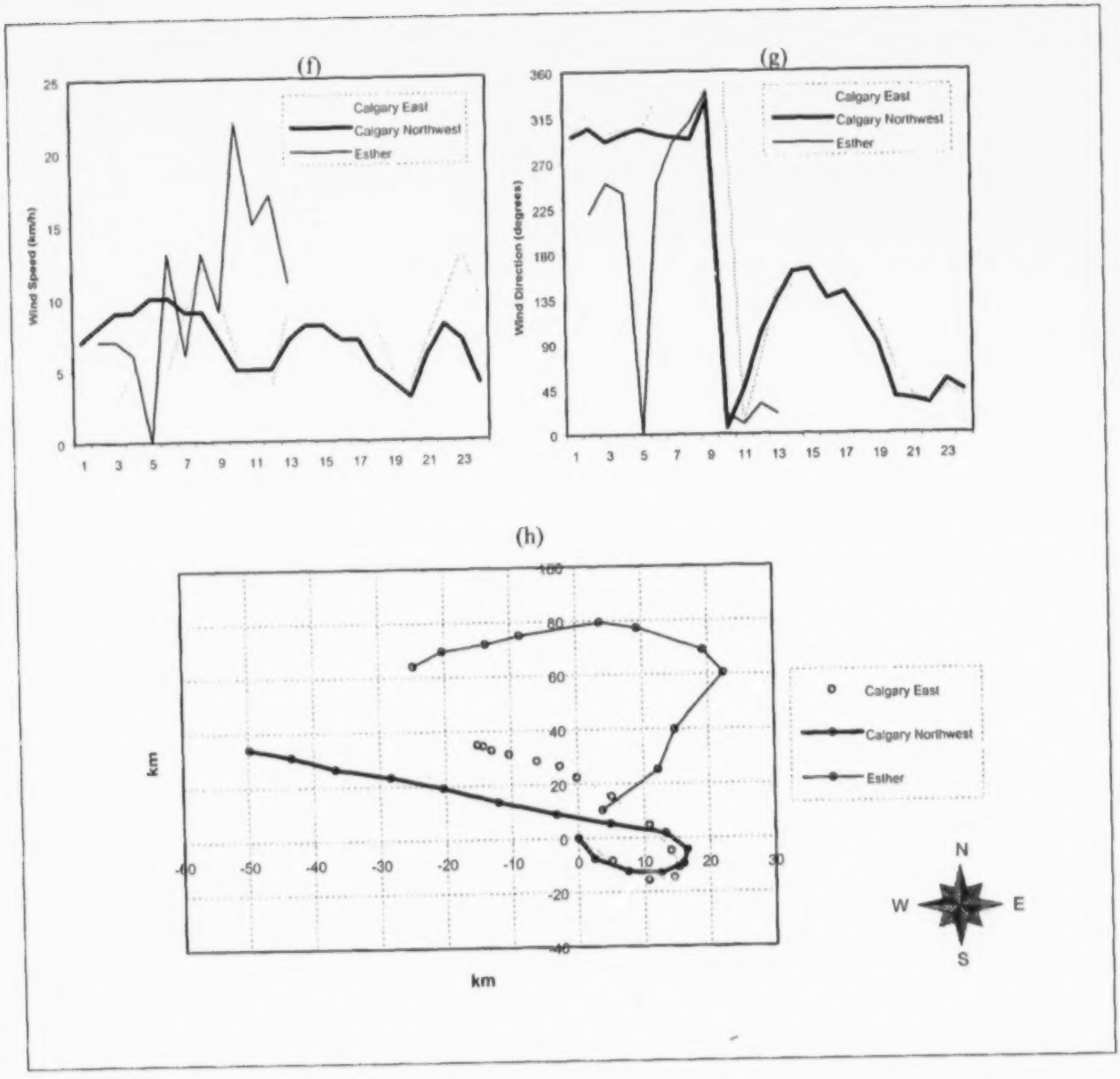

Figure 5.4 (continued)

(f) hourly wind speed on July 27, 1998; (g) hourly wind direction on July 27, 1998; (h) Calgary area back-trajectories on July 27, 1998, 0100h–1400h.

5.4.2 Edmonton Airshed

The air monitoring stations used to represent an Edmonton airshed for 1998 were Edmonton Central, Edmonton East, Edmonton Northwest, Fort Saskatchewan, and Tomahawk. The city of Fort Saskatchewan is 25 km northeast of Edmonton; Tomahawk, which was used as the rural station for comparison, is 88 km west-southwest of Edmonton (Figure 1.1). Ozone values at all five stations were compared; temperature data were available for Tomahawk only.

The ozone episode chosen for analysis occurred on Thursday, July 9, 1998 in the Edmonton area. A 1-hour ozone concentration of 98 ppb was recorded at Fort Saskatchewan at 1700h on this day. A total of four 1-hour exceedances were recorded at the Fort Saskatchewan and Edmonton Northwest stations in the time period surrounding the episode. No 1-hour exceedances were recorded at Edmonton Central or Tomahawk during this period. There were ten 8-hour concentrations exceeding 65 ppb on July 9 at Edmonton East, Edmonton Northwest, and Fort Saskatchewan. Figure 5.5a displays the 1-hour ozone trends from July 8 to 10, 1998 and Figure 5.5b shows the 8-hour ozone trends on July 9. All five stations showed similar 1-hour ozone trends, likely indicating a regional influence. All stations had relatively low ozone concentrations on July 8, but Tomahawk had the highest 1-hour ozone value (46 ppb). Ozone episodes occurred on July 9 at Edmonton Northwest and Fort Saskatchewan, while the lowest ozone values were found at Tomahawk. On July 10, Edmonton Northwest had the highest ozone concentrations, including 8-hour concentrations exceeding 65 ppb, while values were lower at the other sites.

On July 9, 1998, wind speeds in the Edmonton area were light, averaging 4.3 km/h. The average temperature at Tomahawk was 18.2°C and the maximum temperature was 24.4°C (Figure 5.5c). The ozone maximum occurred at 1700h, the same time that the maximum temperature was reached. Concentrations of NO were greater in the urban areas than at Tomahawk (Figure 5.5d). NO concentration peaked at 0600h–0900h. NO_2 concentrations were lowest at Tomahawk and greatest at Edmonton Central and Edmonton East (Figure 5.5e). Figure 5.5f shows variations in the NO_2/NO ratio. Wind direction was extremely variable from station to station and at each individual station (Figure 5.5g). Wind speeds, also extremely variable, peaked just after the ozone episode and were strongest at Tomahawk and weakest at Fort Saskatchewan (Figure 5.5h). Back-trajectories for each station are shown in Figure 5.5i.

Ozone values at Edmonton East were probably lower due to higher NO concentration prior to the episode and subsequent ozone destruction. Tomahawk, which had the lowest ozone and NO_X values during the episode, was not downwind of Edmonton, but rather the winds varied in direction and were the strongest of all stations in the area. Tomahawk likely represents natural rural ozone values and the gradual increase of ozone was probably a result of downward transport of ozone from the tropospheric reservoir, associated with atmospheric mixing.

At Fort Saskatchewan, the winds were light and from the west, then south, prior to the episode, making Fort Saskatchewan downwind of Edmonton. Since conditions included light winds, low NO concentration, and high temperature, photochemical ozone production was probably the main cause of the ozone episode. Transport of ozone and/or ozone precursors (NO_2 and VOCs) from Edmonton may also have contributed. The NO_2/NO peak (Figure 5.5f) does occur prior to

the ozone episode, further suggesting that photochemistry was the mechanism affecting Fort Saskatchewan.

At Edmonton Northwest, winds were from the west and then northeast in the hour before the episode. Wind speeds averaged 1–7 km/h, but dropped to 1 km/h just before the episode. The surface wind patterns do not give much insight into the episode, but the NO_2/NO peak at Edmonton Northwest (Figure 5.5f) occurred at the time of the ozone peak, which is evidence that photochemical ozone formation was the cause of the episode at Edmonton Northwest.

5.4.3 Rural Alberta

Rural ozone values were examined for the May 3–8, 1998 period because of an unusual ozone occurrence. Violet Grove had 1-hour and 8-hour episodes during this period while three other rural stations in the vicinity, Carrot Creek, Steeper, and Tomahawk, did not experience episodes. All four stations are east or northeast of Edmonton. See Table 1.1 or Figure 1.1 for the distances from Edmonton to these stations. Violet Grove lacked ozone data for 0400h on May 5. NO_X data were available only from Carrot Creek and Violet Grove. Solar radiation data were available from Steeper and Violet Grove only, and temperature and wind data were available from all four stations.

Ozone concentrations at each of the rural stations are shown in Figure 5.6a for the period May 3–8. Seven exceedances of the 1-hour guideline (ranging from 86 to 185 ppb) were recorded at Violet Grove on May 3, 4, 5, and 7, 1998, with the majority of the exceedances on May 5. All stations had similar diurnal ozone trends, with a lack of diurnal variation during May 4–6. The highest 1-hour average ozone concentrations were found at Violet Grove and Steeper, while the lowest values of the four stations were found at Carrot Creek (north of Violet Grove and Steeper). Disregarding the ozone episodes, the average 1-hour ozone concentrations at all four stations (ranging from 30 to 60 ppb) was higher than the average values at urban stations during the same period (Figures 5.6b). As with the rural stations, the urban stations had no diurnal ozone variation on May 5, 1998.

In Violet Grove on May 5, 1998, four 1-hour episodes occurred at 0500h and from1800h to 2000h. There were also 8-hour concentrations exceeding 65 ppb on May 5, 1998 (Figure 5.6c). At Violet Grove, 8-hour episodes occurred at 0100h, 0600h–1300h, and 1900h–2400h. Steeper also had 8-hour episodes from 0100h to 0200h.

NO concentrations were low (below 1 ppb) in rural Alberta on May 5 (Figure 5.6d). NO_2 concentrations (Figure 5.6e) were low to moderate on May 5. During the ozone episodes at Violet Grove, NO concentrations peaked at Edmonton Northwest (Figure 5.6f). NO_2 concentrations peaked in the Edmonton area at 0100h and at 1700h on May 5 (Figure 5.6g), both just prior to ozone episodes at Violet Grove. The ozone episode at Violet Grove also coincided with the NO_2/NO peak (Figure 6.5h), which occurred at 1900h. Carrot Creek also had an NO_2/NO peak, but lacked a peak in ozone.

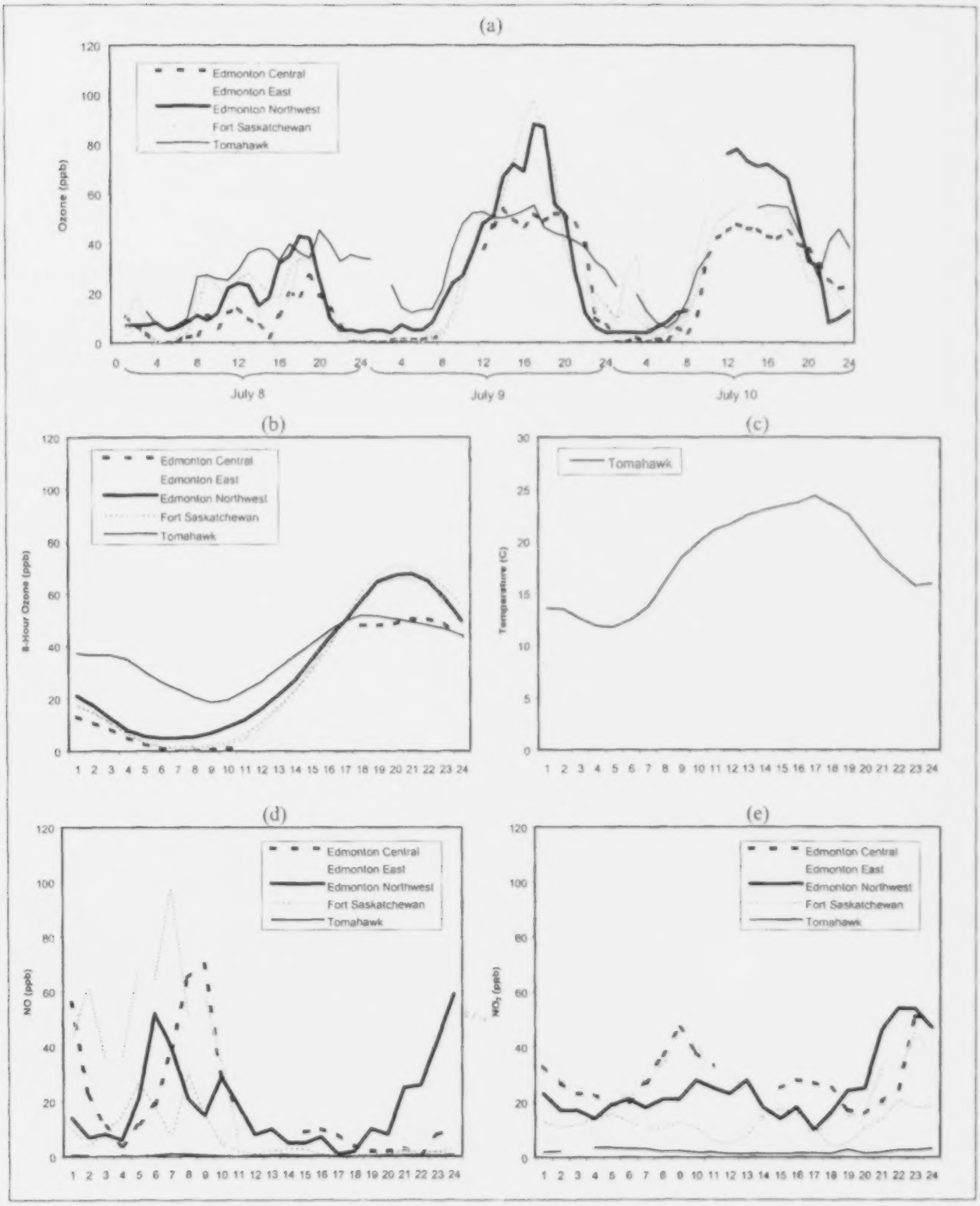

Figure 5.5 Ozone and NO_X concentrations and meteorological conditions in the Edmonton area, July 1998

(a) hourly ozone (July 8, 9, and 10, 1998); (b) 8-hour ozone on July 9, 1998; (c) hourly ambient temperature on July 9, 1998; (d) hourly NO on July 9, 1998; (e) hourly NO_2 on July 9, 1998.

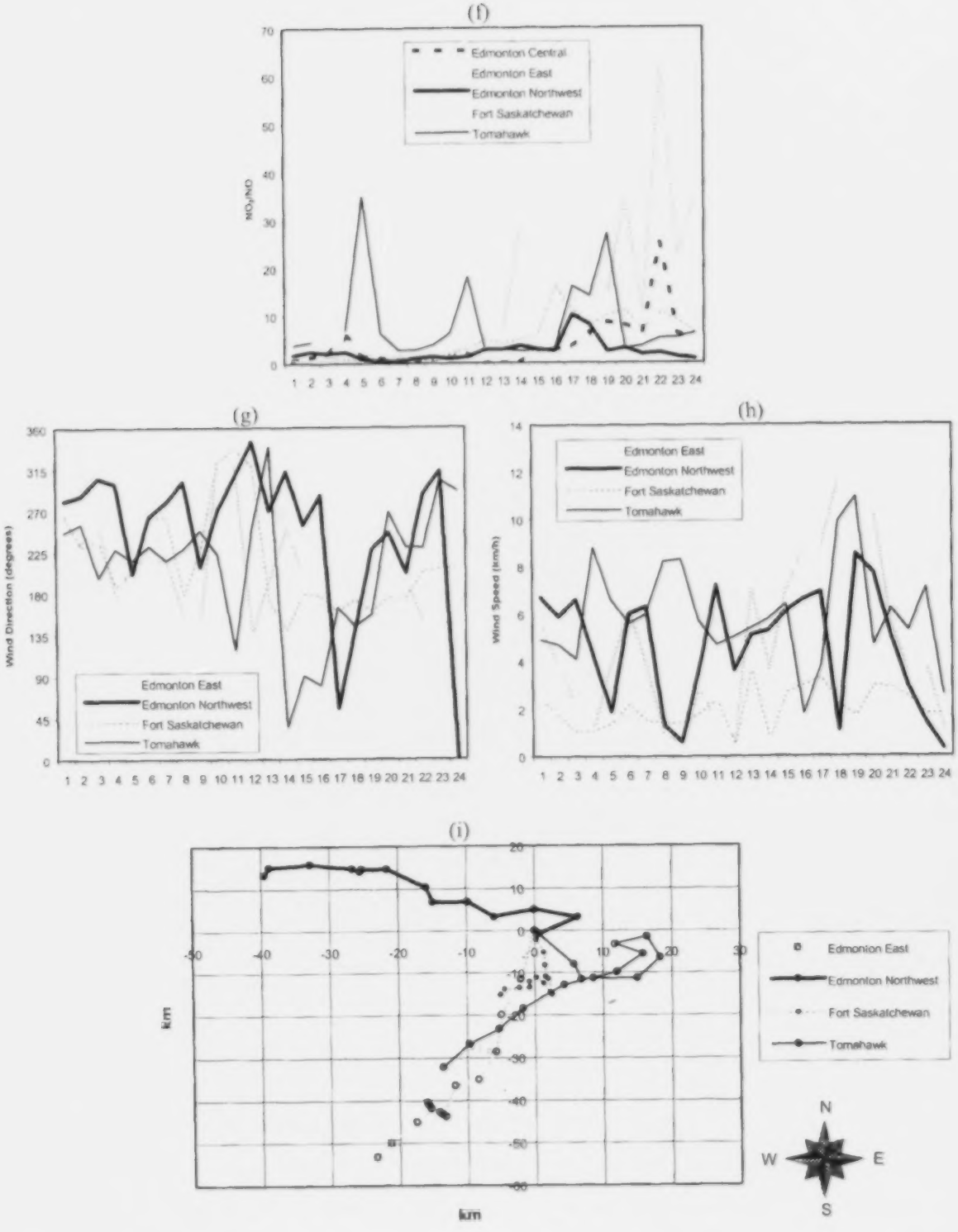

Figure 5.5 (continued)

(f) NO_2/NO on July 9, 1998; (g) hourly wind direction on July 9, 1998; (h) hourly wind speed on July 9, 1998; (i) Edmonton area back-trajectories on July 9, 1998, 0500h–1800h.

All four stations had similar temperature regimes (Figure 5.6i), with a maximum temperature of only 17.0°C (at Carrot Creek). The average temperature on May 5 was 10.7°C. Of all four stations, Carrot Creek and Tomahawk had the highest temperatures, but the lowest ozone concentrations. Both Steeper and Violet Grove had solar radiation peaks, 840 W/m^2 and 1006 W/m^2, respectively (not shown) at 1100h–1500h. However, Violet Grove had an ozone peak with a 5-hour lag time, while Steeper had no increase in ozone following the radiation peak.

All stations showed similar wind patterns (Figures 5.6j, 5.6k, and 5.6l), and northwesterly/ westerly wind that veered around to a northerly/northeasterly wind just prior to the episode. In Violet Grove, winds seemed to be from the north during the 0500h and 1800h–2000h ozone episodes on May 5. Winds were gentle to strong at the four rural stations, averaging 15–35 km/h. However, wind speed decreased in Violet Grove prior to the episode.

Although it does not seem that photochemical ozone formation was favoured in this rural area, NO concentrations were low, limiting ozone destruction, solar radiation was high, and NO_2/NO peaked at the time of the ozone episodes in Violet Grove. Ozone concentration at Violet Grove generally peaked in response to temperature increases (diurnally) in May, but the ozone episodes were not associated with the highest temperature periods (Figure 5.6m).

Ozone transport from Edmonton was possible, considering that Violet Grove was briefly downwind of Edmonton (when winds were from the northeast) prior to the ozone episode at 1800h–2000h. However, Tomahawk is situated between Edmonton and Violet Grove and no elevated ozone values were recorded there. The puzzle here is the inconsistency of ozone values between Violet Grove and the other stations, yet the uniformity of other meteorological variables among the four rural stations.

Some possible causes for the ozone episodes at Violet Grove are:

- Downward mixing of ozone from the upper troposphere.
  With the strong winds in the hours before the episode, increased mixing may have brought natural ozone down from the tropospheric reservoir.

- Numerous forest fires that occurred in the area on May 5, 1998.
  A study by Cheng et al. (1998) concluded that, because forest fires produce NO_2 and ozone, ozone concentrations can be substantially increased downwind of fires. This study also found that the influence of forest fire on air quality was much more prevalent in rural than in urban areas. Therefore, photochemical ozone production could have been enhanced at Violet Grove as a result of upwind forest fires. However, questions remain as to why these fires did not similarly influence the other rural stations in the area.

- Intrusion of ozone from the upper atmosphere (stratospheric intrusion).
  Stratospheric intrusions can be characterized by higher-than-normal average ozone concentrations and lack of diurnal variation (EC, 1998a). All four stations showed little diurnal ozone variation on May 4 and 5. However, the strong winds may account for the lack of diurnal variation. Episodes of stratospheric intrusion can also be characterized by

relatively rapid changes in ozone concentrations, with peaks occurring at times not expected from photochemical processes (Finlayson-Pitts and Pitts, 1986), making intrusion a good possibility as the cause of the episode at Violet Grove.

It is possible that the whole area was influenced by stratospheric ozone and Violet Grove was subject to streaks of stratospheric intrusion. A similar event occurred in Regina, Saskatchewan, where a large ozone episode took place but no events were recorded at the nearest upstream or downstream monitoring stations (Chung and Dann, 1985). The high ozone values of 138-228 ppb in Regina, which were accompanied by strong shifting winds and jet streams, were attributed to stratospheric intrusion.

There is no definitive conclusion as to the source of the ozone exceedances recorded at Violet Grove in May 1998. One possibility is that atmospheric mixing brought ozone from the tropospheric reservoir and/or photochemistry was enhanced by precursors from fires in the area. Photochemistry is a definite possibility considering that both the peak in temperature and the peak in the NO_2/NO ratio at Violet Grove coincided with the ozone peak on May 5. Nevertheless, stratospheric intrusion, although an uncommon event, cannot be ruled out here.

A more definitive resolution may be found with further investigation into:

(i) the exact locations and times of forest fires prior to the episodes,

(ii) industrial emissions in the area,

(iii) wind patterns higher in the atmosphere that may be linked to stratospheric intrusion,

as well as a trajectory analysis for tracking fire pollution in the upper atmosphere.

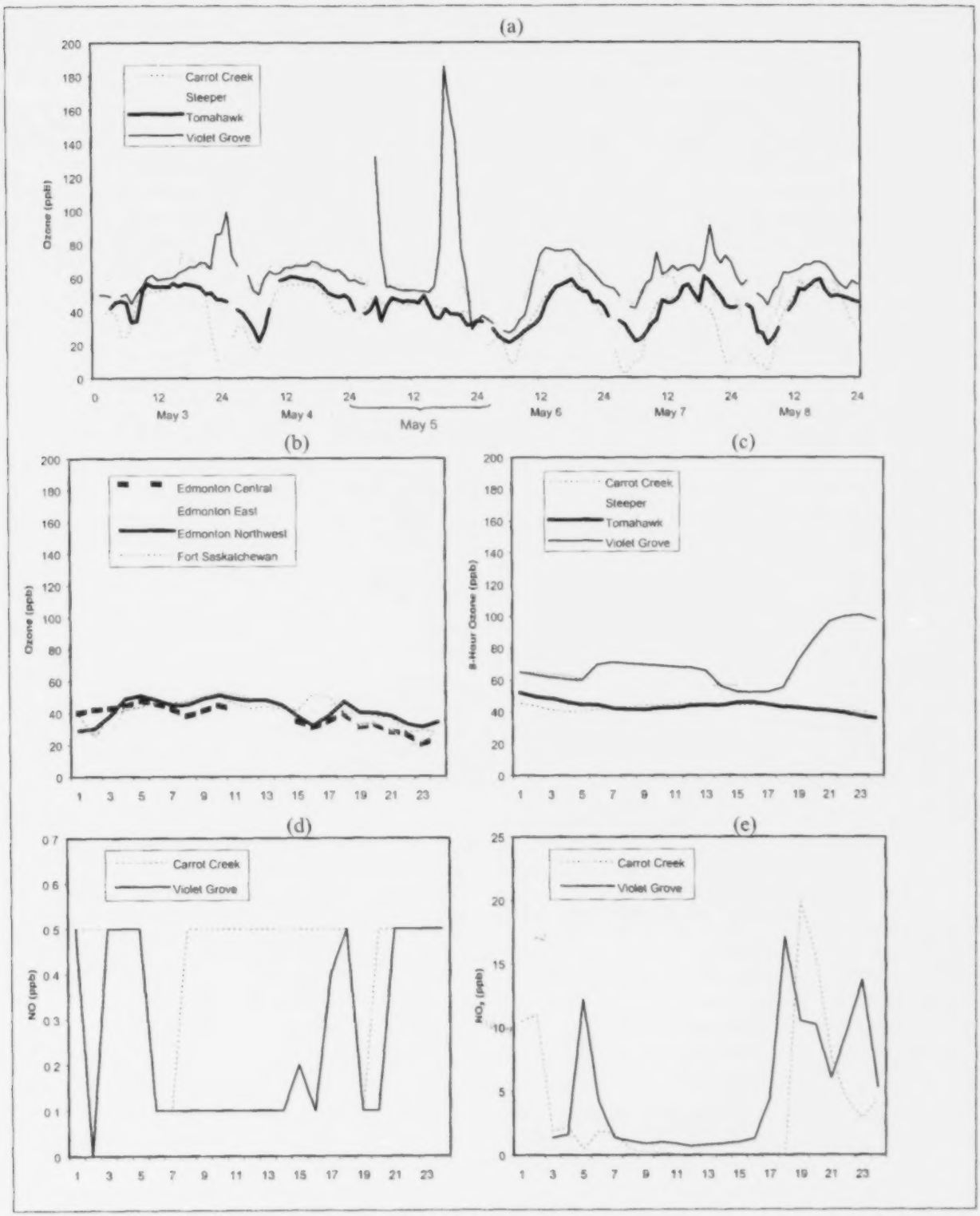

Figure 5.6 Ozone and NO_X concentrations and meteorological conditions in rural Alberta, May 1998

(a) hourly ozone, May 3–8, 1998; (b) hourly ozone in the Edmonton area on May 5, 1998; (c) 8-hour ozone in rural Alberta on May 5, 1998; (d) hourly NO on May 5, 1998; (e) hourly NO_2 on May 5, 1998.

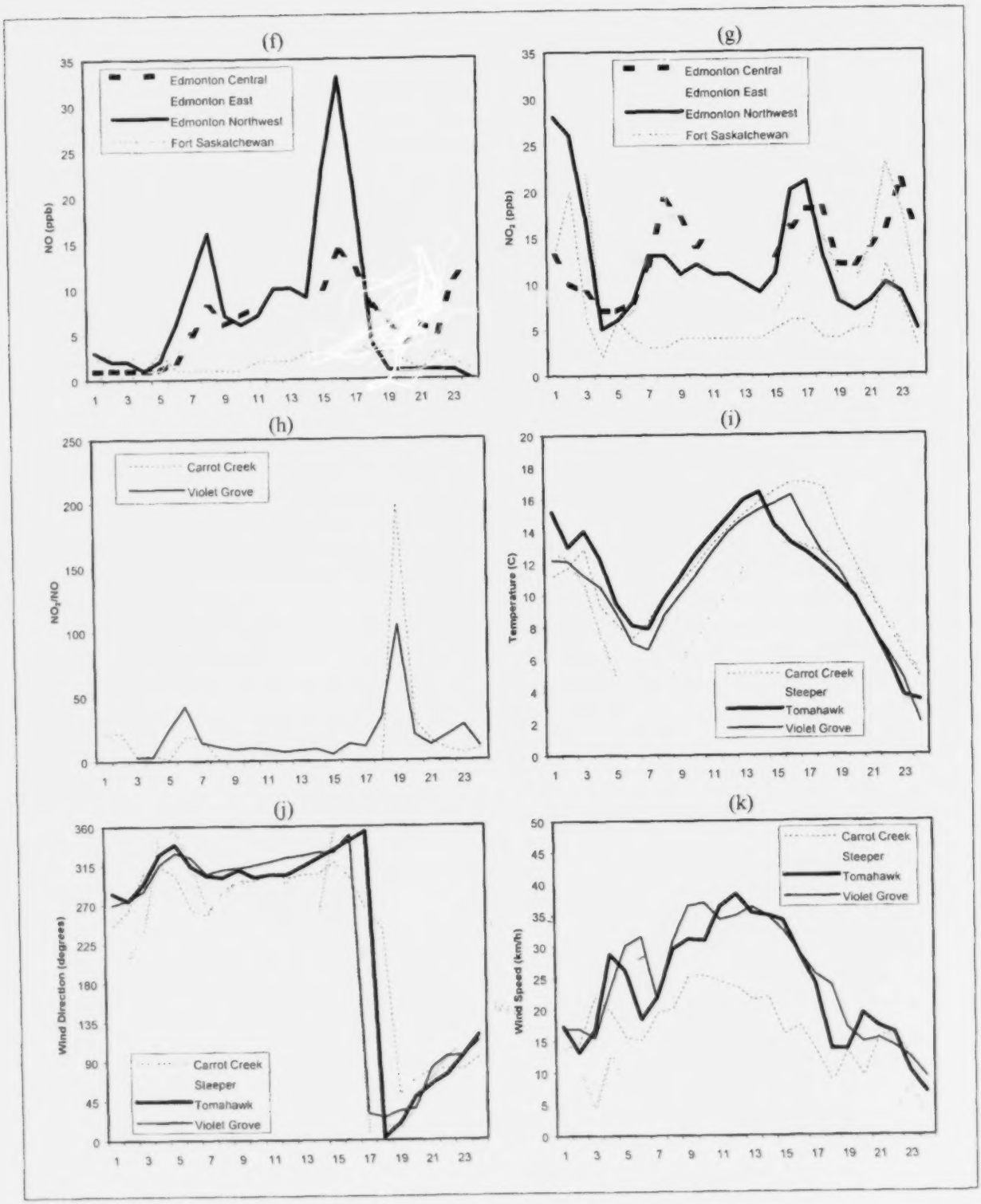

Figure 5.6 (continued)

(f) hourly NO in Edmonton area on May 5, 1998; (g) hourly NO_2 in Edmonton area on May 5, 1998; (h) NO_2/NO on May 5, 1998; (i) hourly ambient temperature on May 5, 1998; (j) hourly wind direction on May 5, 1998; (k) hourly wind speed on May 5, 1998.

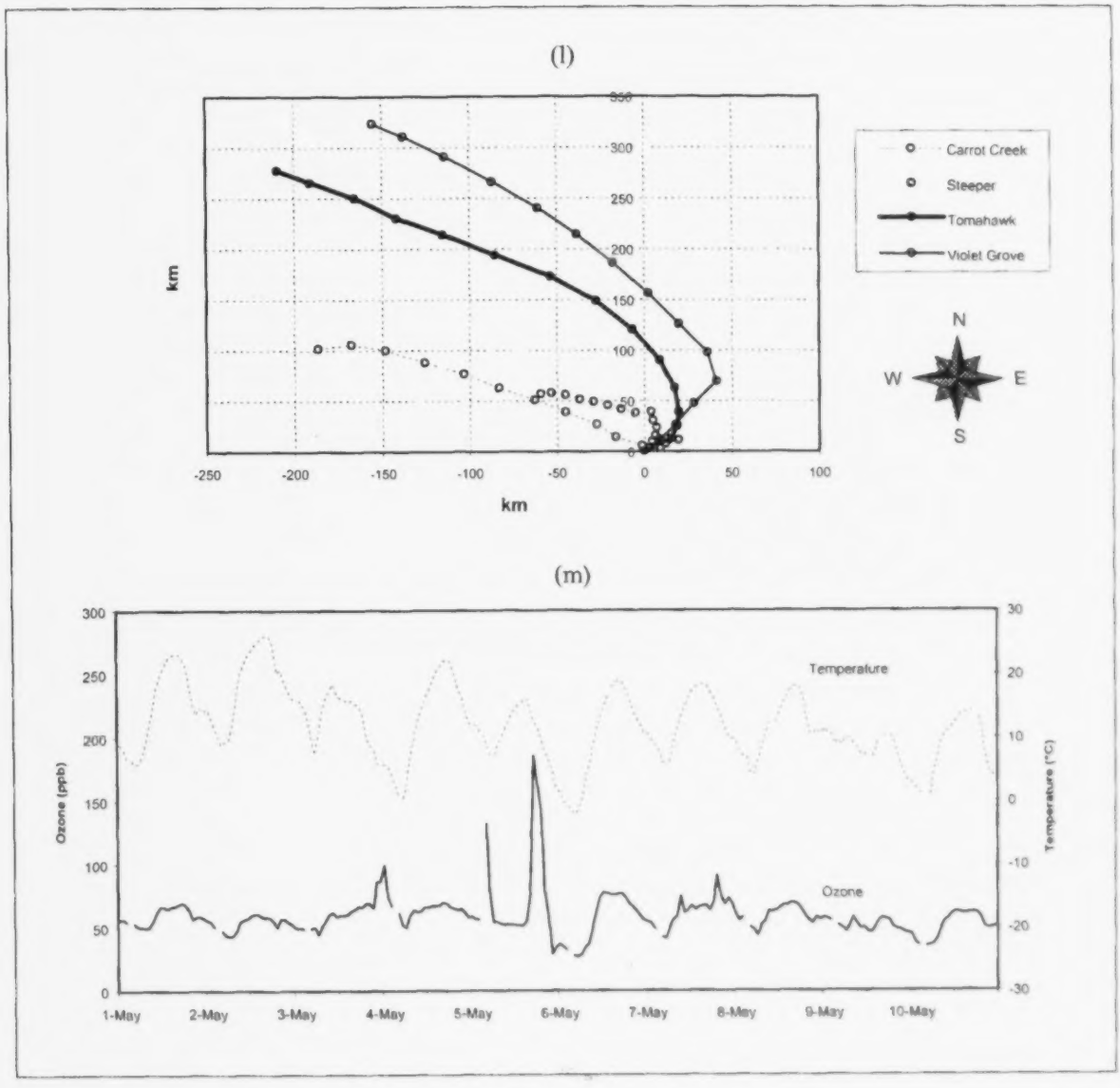

Figure 5.6 (continued)

(l) rural Alberta back-trajectories on May 5, 1998, 0700h–2000h; (m) hourly ozone and temperature at Violet Grove in May 1998.

6.0 METEOROLOGY AND OZONE

Observed ozone concentrations are a result of not only chemistry, but also meteorology. In this section, ground-level ozone concentrations in Alberta are characterized in terms of surface wind speed, wind direction, and temperature. The purpose of this component of the study is to determine whether or not ozone concentrations are dependent on these meteorological variables. A more detailed meteorological analysis could be performed in the future using mixing parameters, since only temperature and surface winds were investigated here.

6.1 Dependence of Ozone Concentration on Wind

In general, the lowest ozone concentrations occurred during periods of light winds, while higher average concentrations occurred during periods of moderate to strong winds at Alberta stations. Wind speed is an indicator of mixing—stronger winds promote more mixing and consequently greater ozone concentrations as a result of downward movement from the upper troposphere. Sandhu (1999) states that lower wind speeds lead to reduced ventilation and a buildup of ozone. However, this idea of greater ozone concentrations with weaker winds refers to photochemical production of ozone in cities, where precursors are present. When examining maximum ozone values in Alberta, the maximum 1-hour concentrations generally occurred during periods of lighter winds. These observations suggest that high average ozone concentration (i.e., in rural areas) is mainly a result of upper tropospheric ozone, whereas discrete maximums (in urban and/or industrial areas) are attributable to photochemistry.

Plots in Figure 6.1 show how average 1-hour ozone concentration varied with wind speed and direction at each Alberta air station over the reference period. Similar ozone-wind trends were seen for 1-hour and 8-hour ozone concentrations. Plots of 8-hour ozone variance with wind are given in Figure AII.1 in Appendix II. Most stations showed a slight ozone–wind speed dependency, with average ozone concentrations increasing as wind speed increased. However, low wind speeds seemed to be required for peak ozone concentrations, as is shown by the maximum concentrations plotted in Figure 6.1. Directionality of the ozone–wind speed dependence is apparent when an ozone trend for one wind direction is different from those for the other directions. Most stations showed either no or very slight directionality of the ozone–wind speed dependence. That is, similar ozone–wind speed trends were seen for all wind directions.

A similar study on the dependence of ozone concentration on wind speed was conducted in some urban areas of eastern Canada by the Canada–United States Air Quality Committee (AQC, 1999). Conclusions about ozone in eastern Canada arising from this study included the following:

- Slower winds accompany higher ozone concentrations.
- Intermediate winds cause higher concentrations downwind of source areas.
- High wind speeds do not cause elevated ozone concentrations in the vicinity of source areas.
- Wind-speed-independent ozone levels imply transported ozone.

The ranges of 1-hour and 8-hour ozone concentrations, occurring at different wind speeds, including the maximum, minimum, and standard deviation, are given in Table AII.2 and Table AII.3 in Appendix II. These ozone values are averaged for all wind directions since all

directions gave similar ozone–wind speed relationships. The variations of mean ozone concentration with wind speed and direction are summarized in Table 6.1 for each Alberta station. Wind directions are given in ranges according to Figure 6.1. Table 6.1 states whether or not average 1-hour and 8-hour ozone concentrations were dependent on wind speed (i.e., ozone concentration increased as wind speed increased) and wind direction. If greater average ozone concentrations were found with specific wind directions, those directions are given in the table. In addition, Table 6.1 gives the wind direction that was found to have the highest general (1-hour and 8-hour) ozone concentrations at each station.

In general, average ozone concentrations at Alberta stations increased with wind speed. Since stronger winds support atmospheric mixing, it appears that the downward transport of natural ozone strongly influences ground-level ozone concentrations in Alberta. The Program Monitoring and Reporting subcommittee of the Canada–United States Air Quality Committee found that speed-independence is indicative of transport-dominated ozone in eastern Canada (AQC, 1999). This cannot be applied in the present case, however, since conditions in western Canada are much different from those in eastern Canada. The east is highly populated with city after city whereas the west is much more sparsely populated. Long-range transport to Alberta is generally not feasible with the Rocky Mountains being upwind.

Out of the stations where ozone had a slight dependence on surface wind direction, 90–180° was the range of directions most commonly accompanied by greater ozone concentrations. However, most wind direction dependence seemed to be apparent at greater wind speeds.

6.2 Dependence of Ozone Concentration on Temperature

Past studies have found that photochemistry is enhanced at higher temperatures (Olszyna et al., 1997). Thus, an increase in temperature results in increased ground-level ozone. Photochemical ozone production is generally promoted at temperatures above 20°C (SNV, 1993).

Temperature data were available for only eight stations in Alberta, all of them rural stations except Fort McMurray. The correlation between ozone concentration and temperature was investigated for these eight stations and estimated for Edmonton stations in order to provide a comparison. The Edmonton stations used in this study did not measure temperature, so temperature data from Tomahawk were used. Historical temperature data for Edmonton and Calgary can be obtained from Environment Canada for study purposes, but these data were not accessible for this particular study.

At all stations in Alberta, 1-hour and 8-hour ozone concentrations increased with temperature. However, there was less ozone-temperature dependence at background stations; Hightower Ridge, for example (Figure 6.2). Figure 6.3 shows the correlation between ozone concentration and temperature at the air monitoring stations in Alberta.

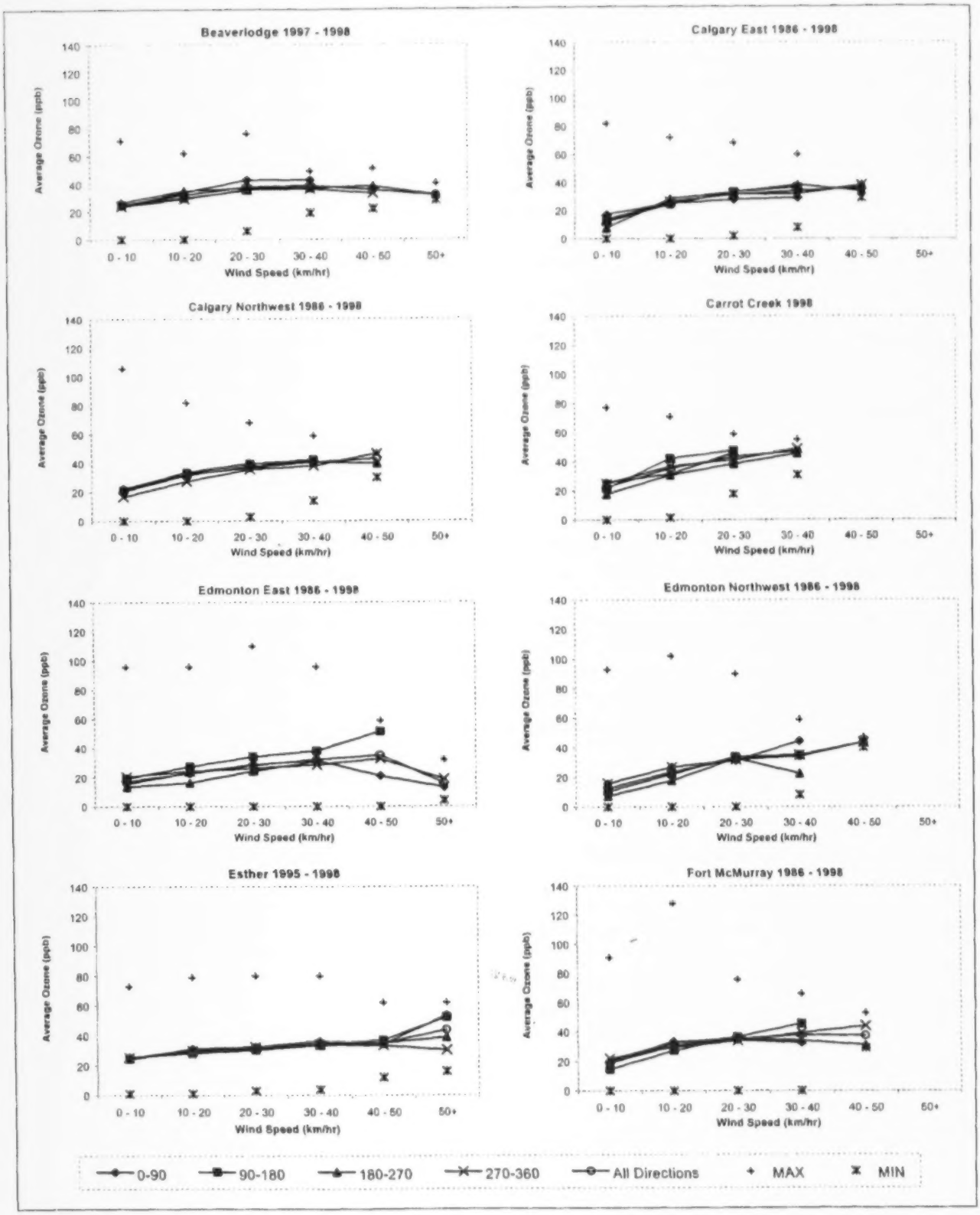

Figure 6.1 1-hour ozone variation with wind speed for different wind directions

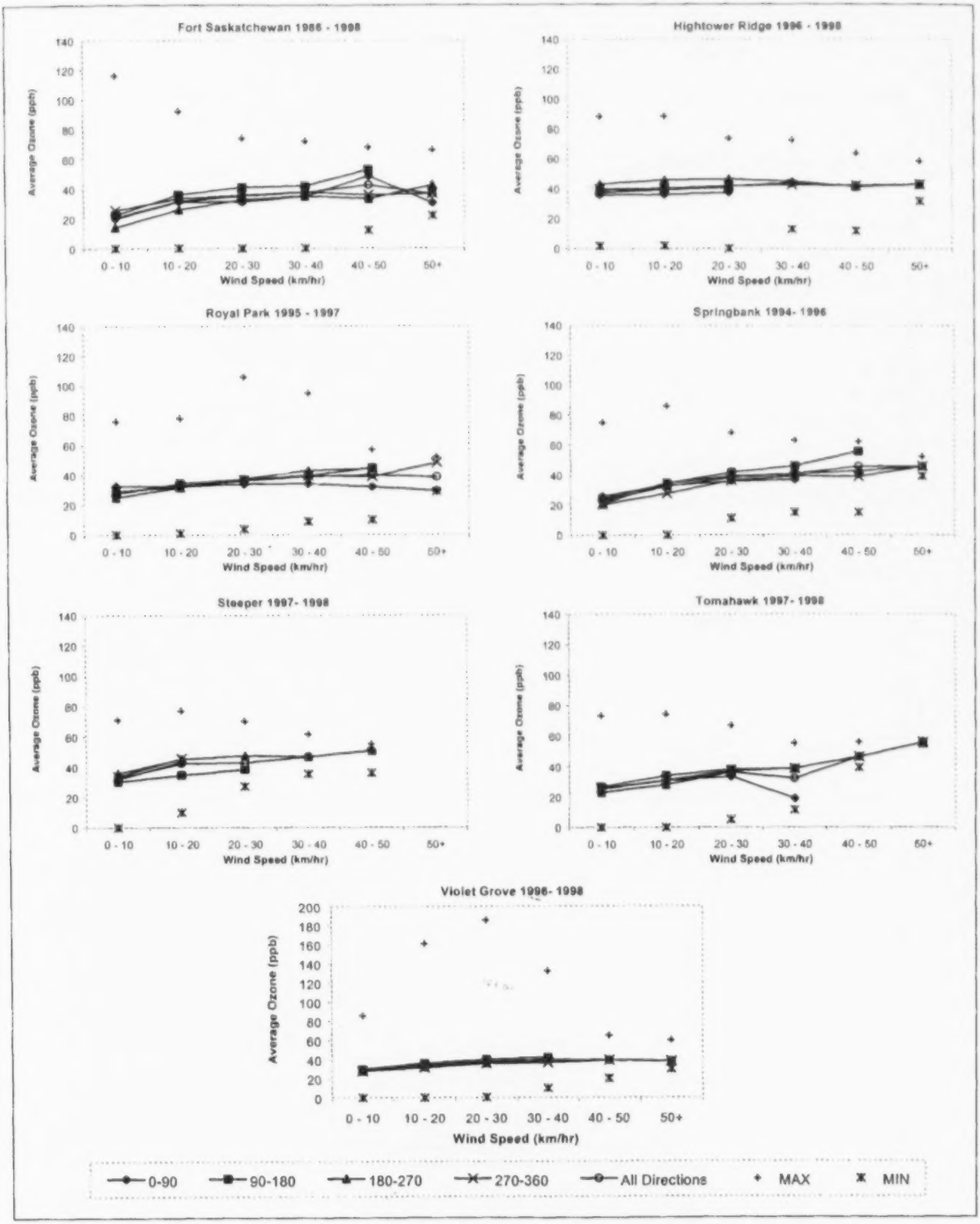

Figure 6.1 (continued)

Table 6.1 Summary of variations in average ozone concentration with wind speed and direction at Alberta stations

Station	1-h average ozone		8-h average ozone		Wind direction(s) giving highest O_3 values
	Wind speed dependence	Wind direction dependence	Wind speed dependence	Wind direction dependence	
Beaverlodge	Up to 20-30 km/h	Slight for 0-90°	Up to 30-40 km/h	0-90°	W
Calgary East	Yes	X	Only over 40 km/h	270-360°, over 30-40 km/h	N
Calgary Northwest	Yes	X	Yes	90-180° and 270-360°, over 20-30 km/h	SW
Carrot Creek	Yes	90-180°	Yes	90-180°, over 10-20 km/h	E and W
Edmonton East	Gradual	90-180°	Little	90-180°	SE and NW
Edmonton Northwest	Yes	0-90° over 20-30 km/h	Yes	X	N and W
Esther	X	0-90° and 90-180° over 40 km/h	X	0-90° and 90-180° over 40 km/h	X
Fort McMurray	Gradual	90-180° over 20-30 km/h	Gradual	90-180° over 20-30 km/h	N
Fort Saskatchewan	Gradual	90-180°	Little	Slight for 90-180°	ESE and WNW
Hightower Ridge	X	X	X	X	SW
Royal Park	X	X	X	Slight for 90-180° winds	X
Springbank	Yes	90-180°, over 20-30 km/h	Slight	X	SE and W
Steeper	Little	X	Little	X	SW
Tomahawk	Yes, except for 0-90° over 20-30 km/h	X	Yes, except for 0-90° over 20-30 km/h	X	SE
Violet Grove	X	X	X	X	X

X - Ozone concentration not dependent on wind.

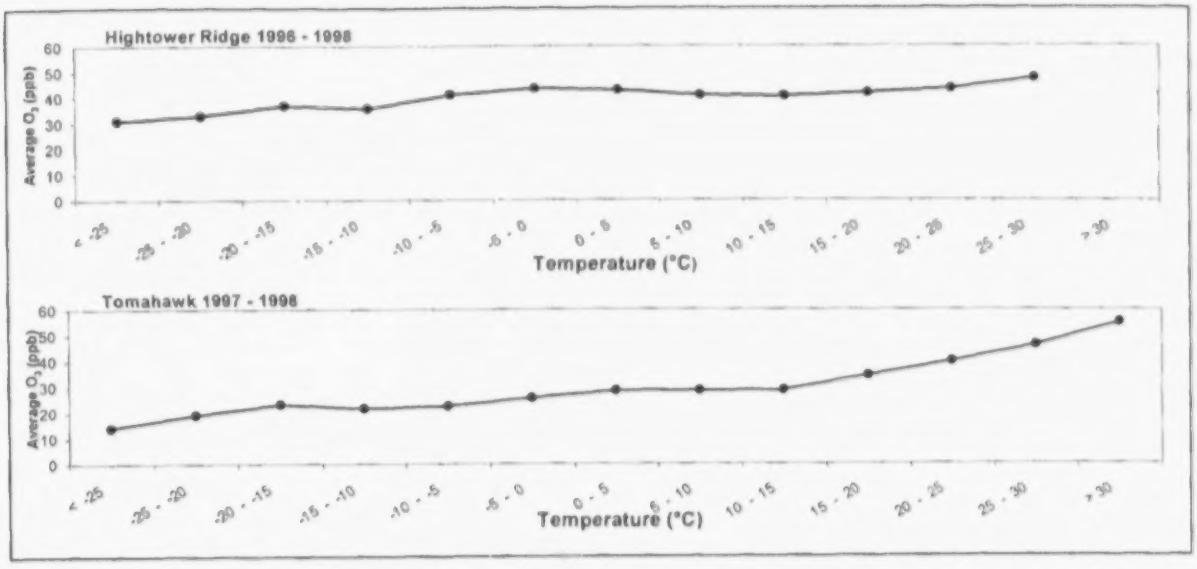

Figure 6.2 Average 1-hour ozone concentrations for different temperature ranges at Hightower Ridge and Tomahawk

All Alberta stations had positive regressions for ozone and temperature, demonstrating that ozone concentrations tend to increase with temperature. However, every station in Alberta had correlation coefficients below 0.5 for 1-hour ozone concentrations, showing that ozone and temperature are not well correlated in Alberta. Because of the large sample size used for Figure 6.2 (600–3000 points), all correlation coefficients are statistically significant at the 1% level.

The station with the highest correlation coefficient for 1-hour ozone and temperature was Fort McMurray at 0.48. Steeper had the lowest correlation, 0.17. The urban stations (Edmonton) had correlation coefficients similar to many of the rural stations for 1-hour ozone. This suggests that ambient temperature influences urban and rural ozone similarly. Ozone concentrations may increase with temperature, but as Walcek and Yuan (1995) state, an increase in temperature will influence ozone formation rates differently in different types of pollutant emission environments (i.e., urban vs rural areas). Ozone concentrations at the two background stations, Hightower Ridge and Steeper, had the least dependence on ambient temperature. This is probably due to the fact that these two stations are at higher elevations than the others and are influenced more by the ozone in the upper atmosphere, as opposed to photochemistry. It is interesting, however, that better correlation was not found between rural ozone and temperature in terms of diurnal mixing. As temperatures increase during the day, atmospheric mixing increases, promoting transport of ozone from the upper troposphere and contributing to background ozone levels.

As was found with 1-hour ozone, there was no strong correlation between 8-hour average ozone levels and temperature. Plots of 8-hour ozone vs temperature are given in Figure AII.2 in Appendix II. All stations had correlation coefficients below 0.42. The station with the highest 8-hour correlation coefficient (0.42) was Edmonton Northwest. Steeper had the lowest correlation coefficient (0.10) for 8-hour ozone and temperature.

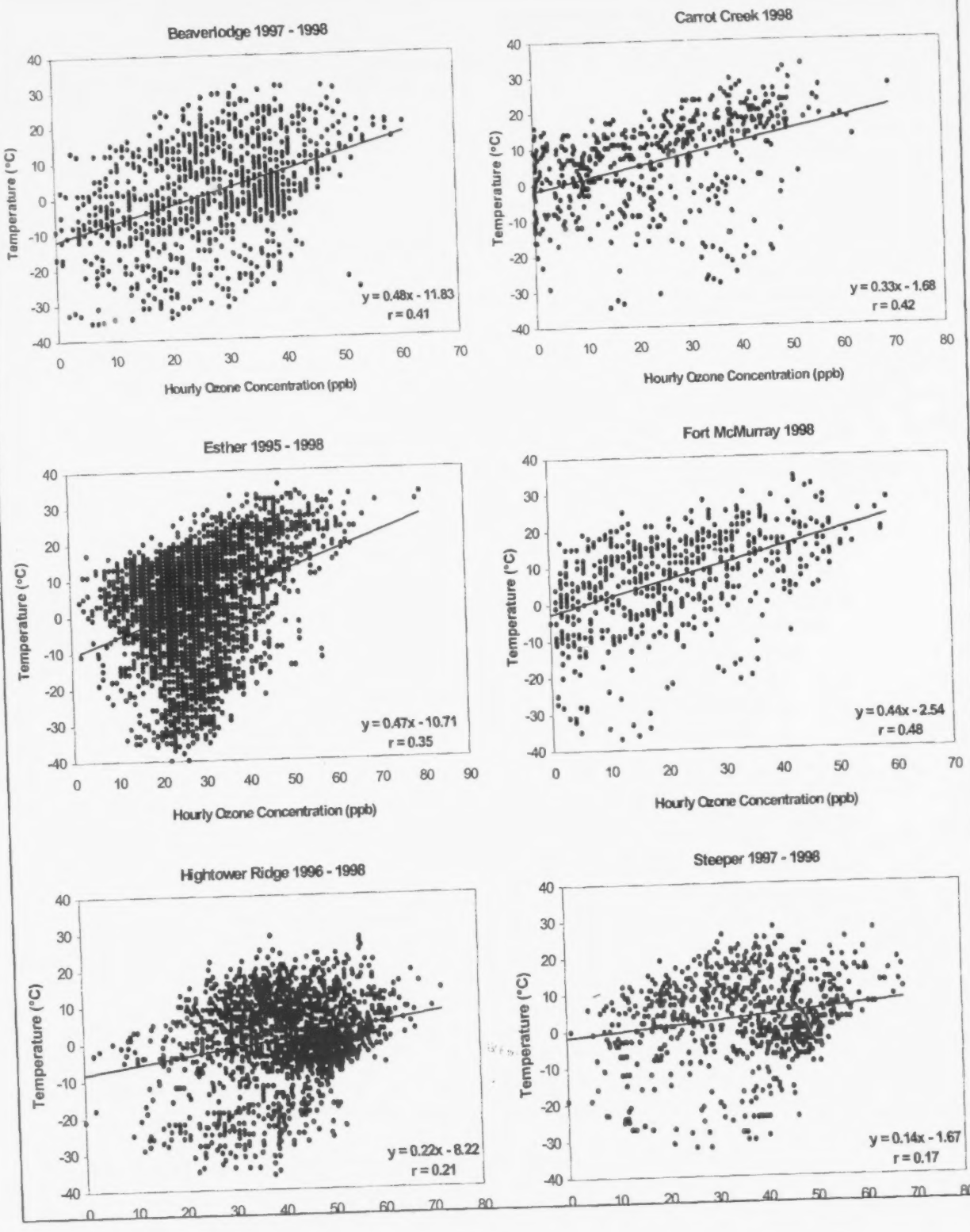

Figure 6.3 **Correlation between hourly ozone concentration and temperature in Alberta**

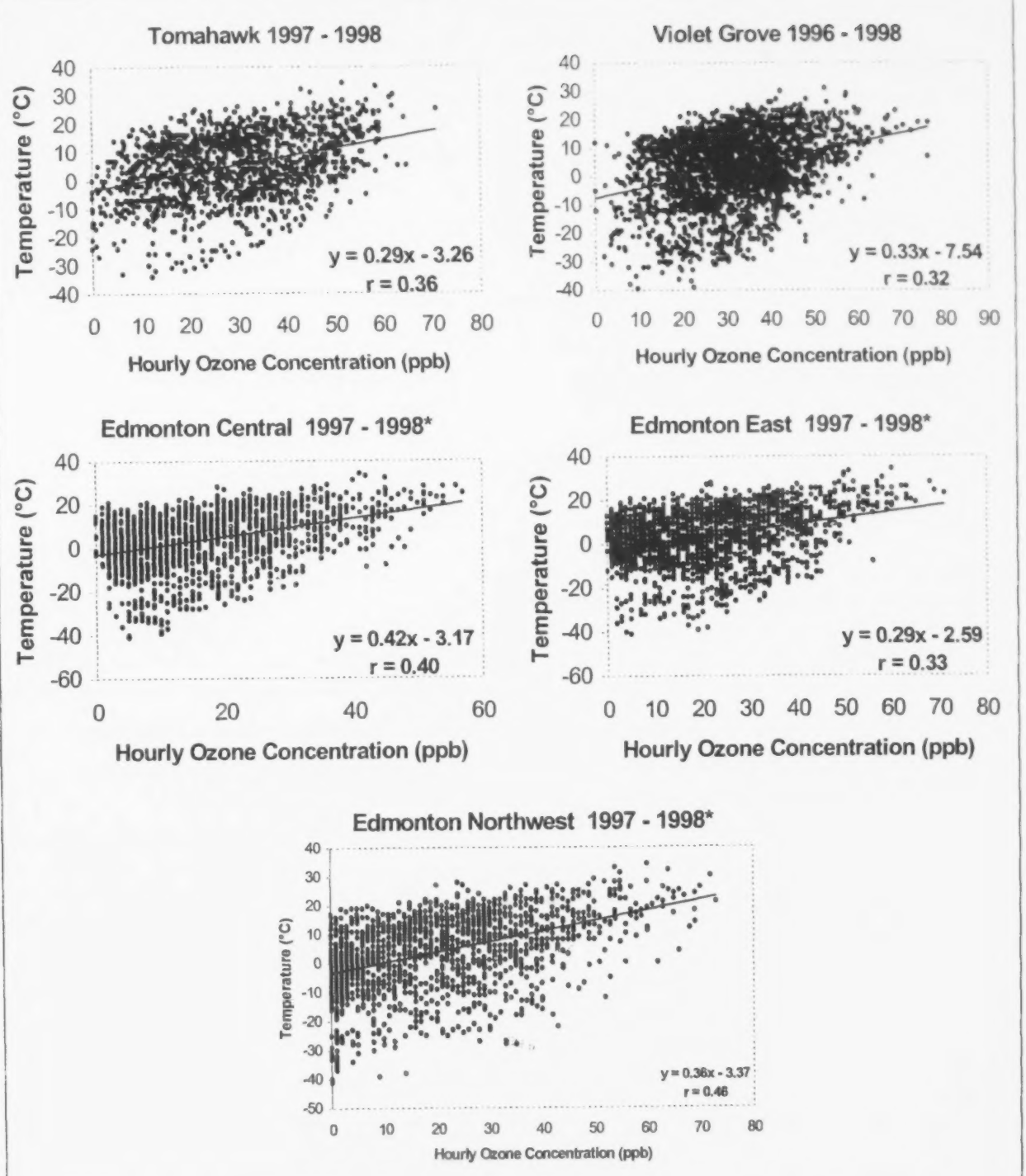
Tomahawk 1997 - 1998
Temperature (°C)
Hourly Ozone Concentration (ppb)
y = 0.29x - 3.26
r = 0.36
Violet Grove 1996 - 1998
Temperature (°C)
Hourly Ozone Concentration (ppb)
y = 0.33x - 7.54
r = 0.32
Edmonton Central 1997 - 1998*
Temperature (°C)
Hourly Ozone Concentration (ppb)
y = 0.42x - 3.17
r = 0.40
Edmonton East 1997 - 1998*
Temperature (°C)
Hourly Ozone Concentration (ppb)
y = 0.29x - 2.59
r = 0.33
Edmonton Northwest 1997 - 1998*
Temperature (°C)
Hourly Ozone Concentration (ppb)
y = 0.36x - 3.37
r = 0.46
* Temperature data used from Tomahawk 1997 - 1998

Figure 6.3 (continued)

The fact that temperature is not well correlated with discrete ozone concentrations suggests that temperature is not a direct indicator of ozone values. Nevertheless, ozone concentration and temperature show better correlation when the mean ozone concentration is plotted against each temperature value. Figure 6.4 below gives two stations as an example of the correlation between mean 1-hour ozone concentration and temperature.

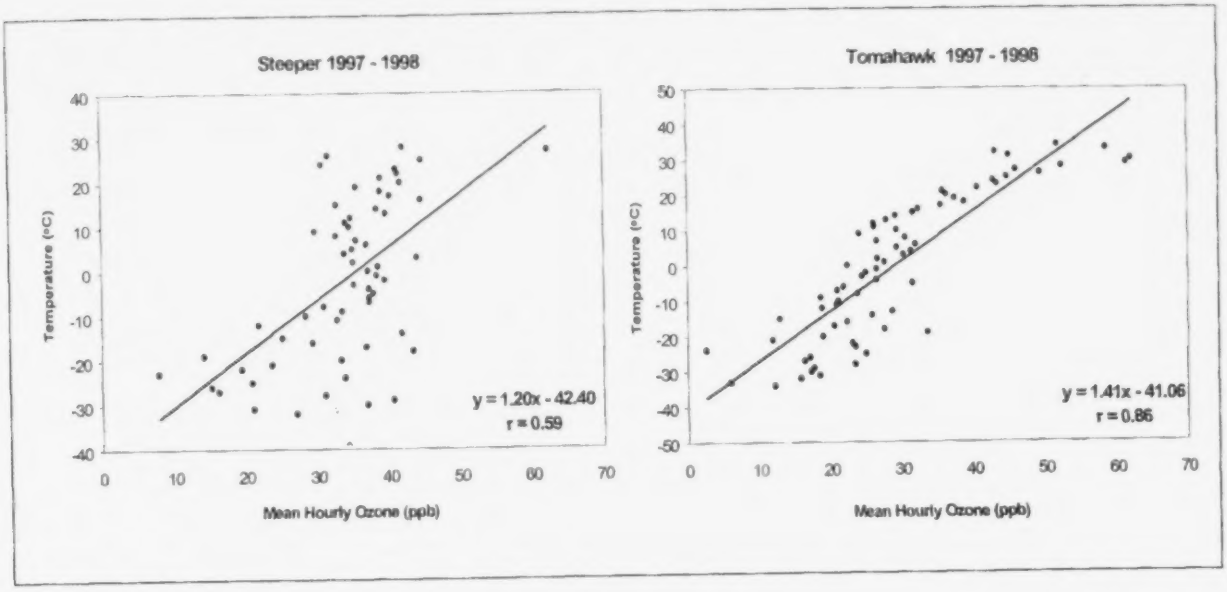

Figure 6.4 Correlation between mean hourly ozone concentration and temperature at two Alberta stations

By using mean ozone concentrations for each temperature value, the correlation coefficient for Steeper increased from 0.17 to 0.59 and Tomahawk's correlation increased from 0.36 to 0.86. Of course, by averaging values one decreases the number of data points; however, there were sufficient data points to show that the correlation between average temperature and ozone concentration is statistically significant at the 1% level. Overall, results from this brief analysis show that temperature alone cannot predict ozone concentration.

7.0 APPLICATION OF CUMULATIVE INDICES TO ALBERTA OZONE LEVELS

Ozone is generally accepted as being the most phytotoxic of criteria pollutants (A&WMA, 1991). Exposure to ozone can result in damage to foliage and can affect plant growth and productivity. According to Tom et al. (1987), the lowest limit for injury for some vegetative species under ordinary conditions is reached following several hours of exposure to an ozone concentration in the range 20–50 ppb,.

Plants show wide differences in their sensitivities to ozone and their response is proportional to exposure time (Horvath et al., 1985). Cumulative ozone indices have been developed in attempts to describe vegetative responses to ozone. These vegetative indices are cumulative in that they involve a summation of hourly values, provided that criteria associated with the index are met.

7.1 SUM and AOT – Purpose and Methodologies

The SUM index is a cumulative exposure index. It is one way of expressing ozone exposure–vegetation response relationships (EC, 1998a). SUMxx is the sum, in ppb-h, of all hourly concentrations at or above a given ozone concentration (xx). The SUM index is calculated over the time period 0800h–1959h (the average hours of daylight). For example, SUM60 is the sum of hourly ozone concentrations at or above 60 ppb between 0800 and 1959h. The SUM index is seasonal in that the calculation involves a rolling sum of concentrations over 3-month periods (normally a growing season).

The AOT index is also a cumulative exposure index for natural vegetation. However, the AOT index is a seasonal censored sum of hourly concentrations above a threshold level. That is, only the concentration amount above the threshold is counted in the summation process, and not the entire concentration as with the SUM index. The AOT40 value is calculated by subtracting 40 ppb from each hourly concentration that exceeds 40 ppb during daylight hours (0700h–2100h as default). The resulting values are summed to give an AOT value in ppb-h. To illustrate, an hourly reading of 65 ppb between 0700h and 2100h contributes 25 to the AOT40 summation process. The 40-ppb level was chosen because of a theory that ozone concentrations above 40 ppb occur due to anthropogenic inputs (EC, 1998a).

7.2 SUM and AOT Indices in Alberta

This study examined SUM40, SUM50, SUM60, SUM70, and AOT40 indices for air monitoring stations in Alberta. The seasonal (3-month) SUM and AOT indices were compared between stations. Tables AIII.1 through AIII.5 in Appendix III contain seasonal averages of each of the above cumulative indices for all Alberta stations.

In Alberta, SUM40 values were much larger than the other indices investigated. This is because, in Alberta, a large number of ozone observations occur in the 40–50 ppb range. Values of the next index, SUM50, were greatly reduced in magnitude in comparison to SUM40. Table 7.1

gives the general range of seasonal (3-month) SUM and AOT values at Alberta stations, and gives the stations with the greatest 3-month values, averaged over all years of data.

Table 7.1 Average ranges of seasonal (3-month) SUM and AOT values in Alberta

Index	Range of seasonal index values
SUM40	0 ppb-h → 43 518 ppb-h at Hightower Ridge
SUM50	0 ppb-h → 28 116 ppb-h at Hightower Ridge
AOT40	0 ppb-h → 11 571 ppb-h at Hightower Ridge
SUM60	0 ppb-h → 7 156 ppb-h at Steeper
SUM70	0 ppb-h → 1 513 ppb-h at Fort Saskatchewan

Figure 7.1 compares the average SUM and AOT indices at stations in Alberta. The SUM 70 index had either very small or null values for stations in Alberta, since there were few 1-hour ozone concentrations exceeding 70 ppb. The only stations with non-zero SUM70 values were Fort McMurray, Fort Saskatchewan, and Violet Grove. The SUM60 index was also low in magnitude, but had values greater than the SUM70 index, and rarely had null values. The highest seasonal SUM60 value in Alberta, 31 133 ppb-h, was found in Fort McMurray during March–May of 1990. This SUM60 value can be attributed to seven exceedances of the 1-hour ozone guideline, which occurred in April of 1990 at Fort McMurray. The cumulative indices have large values when there are many exceedances of the 1-hour ozone guideline during a three-month averaging period (seasonally). Overall, the highest indices were calculated at Fort McMurray, Fort Saskatchewan, Hightower Ridge, and Steeper. In any event, Hightower Ridge is a background station and Steeper has limited vegetation.

Alberta stations share similar seasonal SUM and AOT trends: peaks in the spring/summer and lows in the winter. Urban stations tend to have a peak in May or June with lows occurring in October–December or January. Rural stations have a seasonal peak in March–May with a low in August–October for some stations and a trough in November–January for others. Figure 7.1 illustrates the difference between seasonal trends at rural and urban stations. Hightower Ridge and Steeper have two seasonal SUM/AOT peaks, one in April or May and another in December or January. These rural stations have ozone episodes in the fall/winter as well as spring and the seasonal SUM and AOT trends follow the trends of 1-hour ozone peaks. The urban stations generally have a 1-hour ozone peak in the springtime, and hence have just one SUM or AOT peak in the spring.

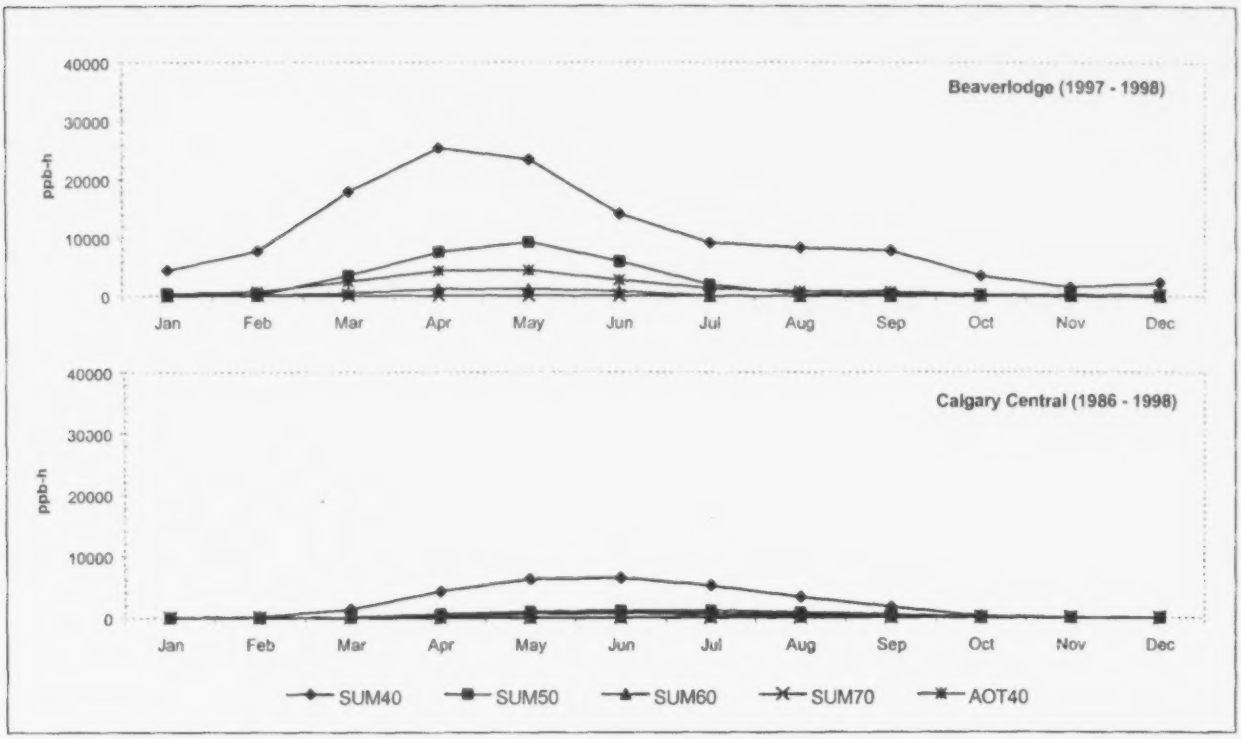

Figure 7.1 Average seasonal (3-month) SUM and AOT values at Alberta stations

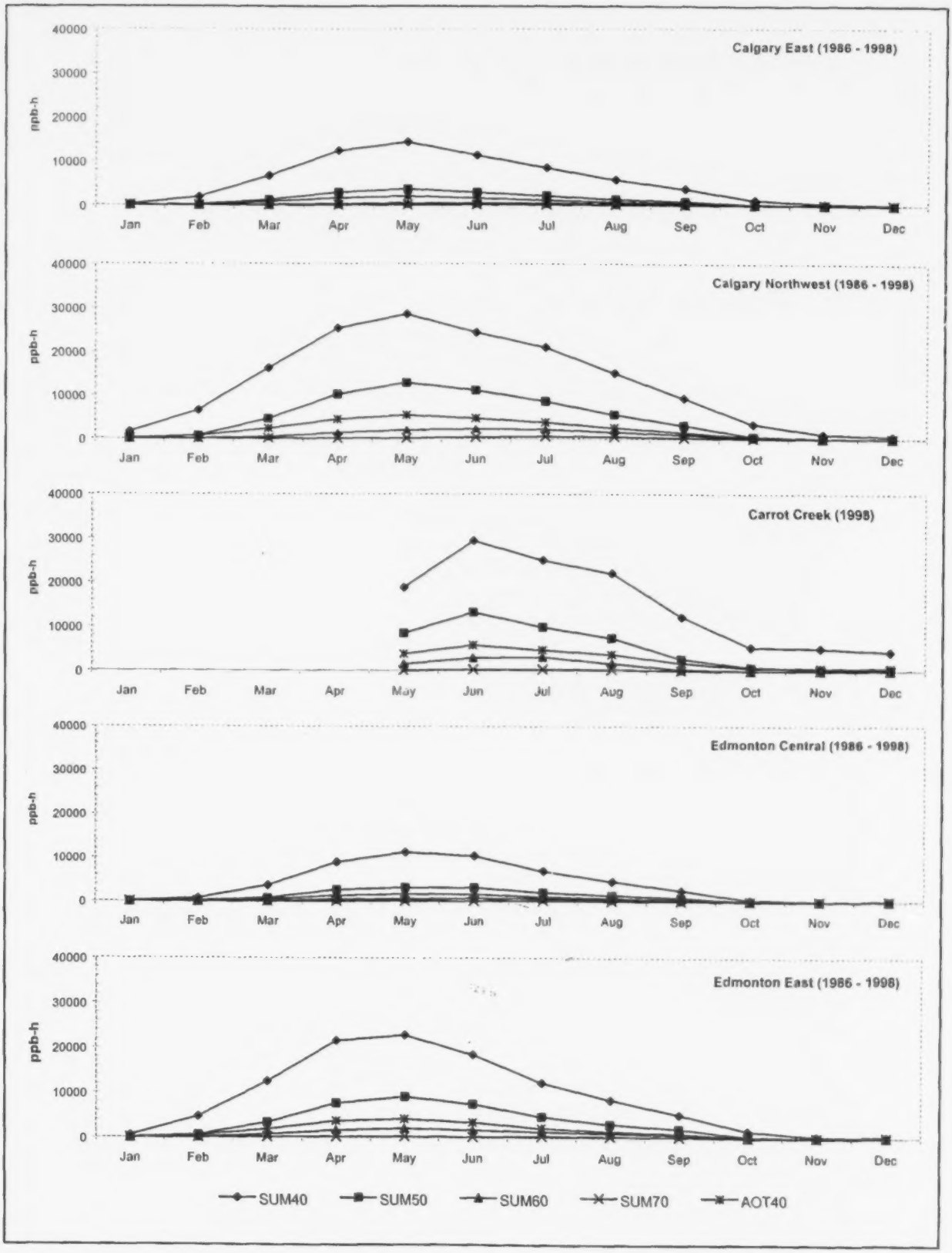

Figure 7.1 (continued)

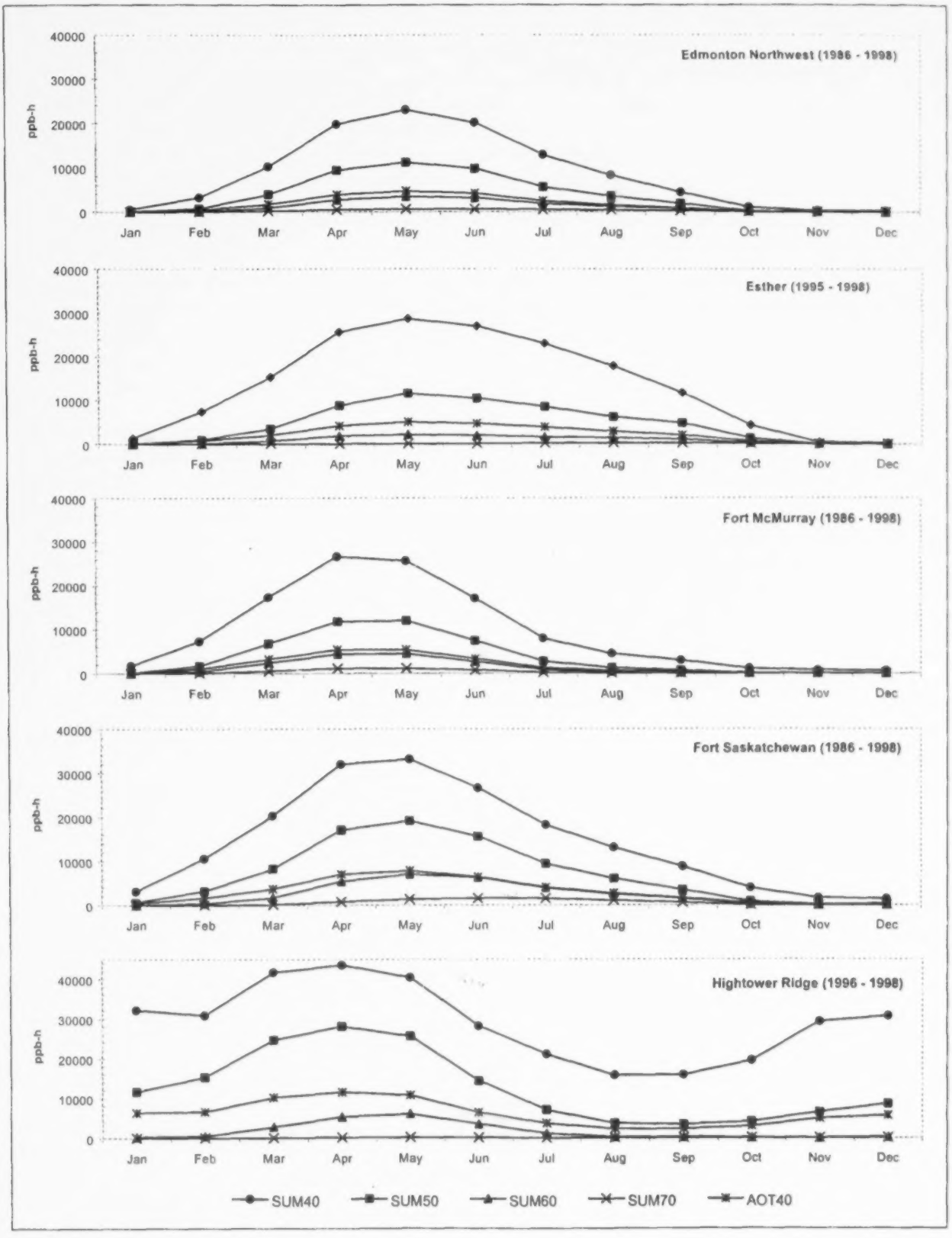

Figure 7.1 (continued)

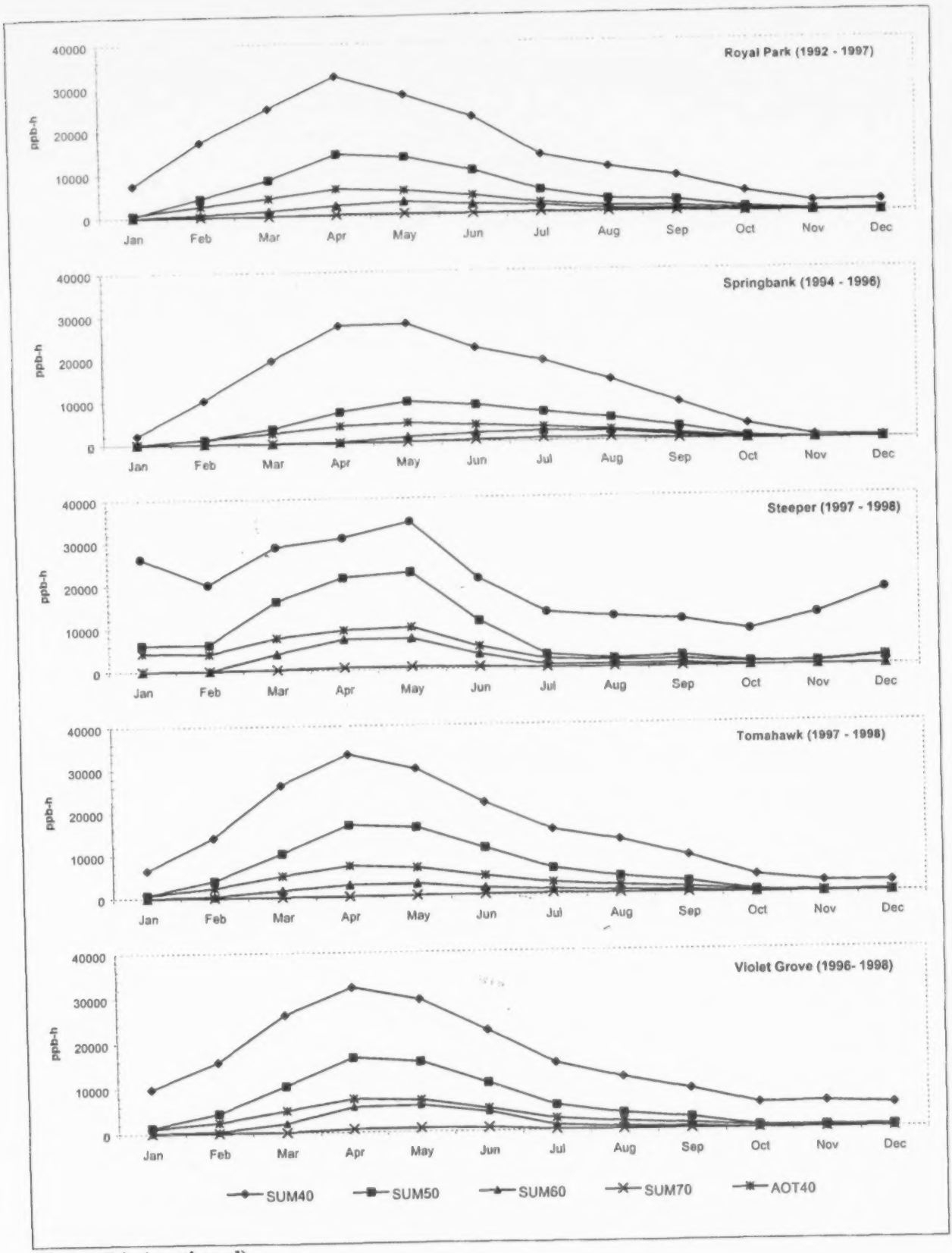

Figure 7.1 (continued)

The seasonal SUM60 (3-month running average) seems to be the index most often used to formulate vegetative reference levels. According to participants at a 1996 workshop held in Raleigh, North Carolina on ecological-based ozone concerns, concentrations above 60 ppb are well correlated with biological response to ozone such as foliar injury, growth effects, and crop yield reductions (A.S.L. & Associates, 1999). It must be noted, however, that correlation does not mean cause and effect. The various vegetative indices, their usefulness, and their ability to predict vegetative responses to ozone have been a subject of discussion and debate worldwide.

The International Specialty Conference on Tropospheric Ozone and the Environment (1990) examined results from the evaluation of ozone exposure indices. Analyses from this conference led to the suggestion that the sum of all hourly concentrations equal to or above 60 ppb (SUM60) may have potential for use in a standard-setting process, but that no single exposure index is best for all vegetative species (A&WMA, 1991). Alberta has not adopted the use of cumulative ozone indices, but rather continues to use an hourly guideline for ozone.

Lefohn et al. (1991) report that the efficiency of the SUM index is limited since it does not take into consideration the difference in weighting of the lower hourly average ozone concentrations (which may affect plants) from the weighting of higher values. Two approaches attempt to addresses this concern, the W126 and the CFD indices, which were not examined in this study.

The W126 is a form of concentration-weighted cumulative index using a sigmoidal weighting function. It includes hourly ozone concentrations as low as 40 ppb, has an inflection point (abscissa value with sigmoid weight of 0.5) of about 65 ppb ozone, and applies an equal weighting of 1 for values at approximately 100 ppb and above. Similar to the W126, the CFD (Cumulative Frequency Distribution) approach considers the potential effect of ozone at 50-87 ppb.

7.3 SUM and AOT Guidelines

The following are SUM60 and AOT40 reference levels that have been set or proposed by different government working groups in recent years. They are examined here only as a means of comparing the vegetative indices among Alberta stations. These reference levels are not being recommended for application in Alberta at this time, since they have not been fully examined with respect to Alberta vegetation.

(a) The following SUM60 reference level was recommended by the Vegetative Objective Working Group to protect eastern Canadian agricultural crops from ozone exposure (EC, 1997b). This level was set to address season-long impacts on growth and productivity and to provide protection to vegetation at the lowest level of scientific certainty (10% yield or biomass loss for 95% of the experimentally evaluated plant species). The crop species evaluated, all of which are grown in central Canada (Ontario), were corn, kidney bean, peanut, potato, sorghum, soybean, tobacco, turnip, and wheat. The only species in this list that are of commercial value in Alberta are corn, potato, and wheat.

Maximum rolling 3-month, 12-hour (0800–1959h) SUM60 not to be exceeded during April to September in any year	⇒ 6600 ppb-h

Nine Alberta stations exceeded the above reference level over the 1986–1998 period. These stations were Fort Saskatchewan, Edmonton Northwest, Fort McMurray, Esther, Violet Grove, Edmonton East, Hightower Ridge, Steeper, and Royal Park. These exceedances generally occurred from March through July. Average seasonal SUM60 values are displayed at the end of this section in Figure 7.2.

(b) The Federal-Provincial Working Group on Air Quality Guidelines and Objectives identified SUM60 values to predict different degrees of vegetation protection. The following are SUM60 values based on experimentation done by NCLAN (the National Crop Loss Assessment Network), a U.S. program (EC, 1997b). The crops evaluated were corn, kidney bean, peanut, potato, sorghum, soybean, tobacco, turnip, and wheat. These crops were grown in open-top chambers, which attempt to simulate ambient conditions, and an assessment was made of the response of the plants to ambient ozone (EC, 1997b). The following SUM60 values were required for protection of a percentage of a crop, ranging from 50% to 100%. Alberta stations are listed beside the SUM60 level that they met, on average, over their respective data periods.

% of NCLAN Crops Protected	3-month SUM60 (ppb-h)	
100	2 900	⇨ Calgary Central, Calgary East, Calgary Northwest, Edmonton Central, Edmonton East, Beaverlodge, Esther, Springbank, Tomahawk
95	6 600	⇨ Edmonton Northwest, Fort McMurray, Carrot Creek, Hightower Ridge, Royal Park, Violet Grove
90	7 400	⇨ Fort Saskatchewan, Steeper
80	10 000	
75	12 300	
50	22 400	

(c) As a result of the NO_X/VOC Science Program, Canadian working groups proposed adoption of a National Ambient Air Quality Objective (NAAQO) for ozone in the form of a SUM60 index (A.S.L. & Associates, 1999). The following season-long LOAEL (lowest observed adverse effect level) was set to protect agricultural crops and trees in Canada against damage by ozone. This reference level, like the above two (a and b), is based upon NCLAN data.

Rolling 3-month SUM60 during daylight period (0800h–1959h) for April to September	⟹	5900–7400 ppb-h

On average, no Alberta air stations exceeded the proposed NAAQO range stated above for SUM60 (Figure 7.2). Three stations were within the 5900–7400 ppb-h range: Fort Saskatchewan, Hightower Ridge, and Steeper. The remaining Alberta stations had average SUM60 values below this range over their respective data periods. To compare seasonal SUM60 values at Alberta stations to the above LOAEL, Table 7.2 indicates where Alberta stations fell in terms of this proposed SUM60 range—the years within, below, and above the range. Six stations, Edmonton East, Edmonton Northwest, Fort McMurray, Fort Saskatchewan, Hightower Ridge, and Violet Grove exceeded the upper limit of 7400 ppb-h at some point(s) in their respective data periods. The remaining 11 stations were within or below the LOAEL in all of the years examined.

(d) Critical levels (CL), or concentrations above which adverse effects may occur on receptors such as vegetation, were defined for ozone at a workshop in Kuopio, Finland in 1996 (EC, 1997b). One CL was defined for use as a long-term indicator of the degree of risk to natural vegetation and agricultural crops in areas of Europe. However, after further investigation, this level, which is in the form of an AOT40 index, is currently being used to define areas of potential risk, and not as a predictor of effects.

Running 3-month AOT40 value calculated for daylight hours (0700h–2100h as a default)	⟹	3000 ppb-h

Considering average seasonal AOT40 values (Table AIII.5 in Appendix III), most Alberta stations exceeded the above critical level. Most of the AOT40 values exceeding 3000 ppb-h were calculated for March–August in the average year. Calgary Central was the only station that did not have an AOT40 value exceeding the suggested CL at some time over the reference period. Fort McMurray had the highest seasonal AOT40 value, 17 422 ppb-h, in March–May 1990.

Alberta has high background ozone levels in relation to other regions, largely as a result of upper tropospheric ozone input. For this reason, Alberta stations did not meet the levels of the vegetative indices explored here over the reference period. However, many of the species used to obtain these levels are not grown in Alberta. In addition, the levels investigated here were based on statistical results for vegetative species grown in chambers, and were not based on cause-effect relationships.

Cumulative ozone indices have not been accepted for use in Alberta. There is currently no vegetative guideline for Alberta based upon the SUMxx and AOTxx indices. The 1-hour, 82 ppb, guideline is still applied in Alberta for the protection of health and the environment, including vegetation.

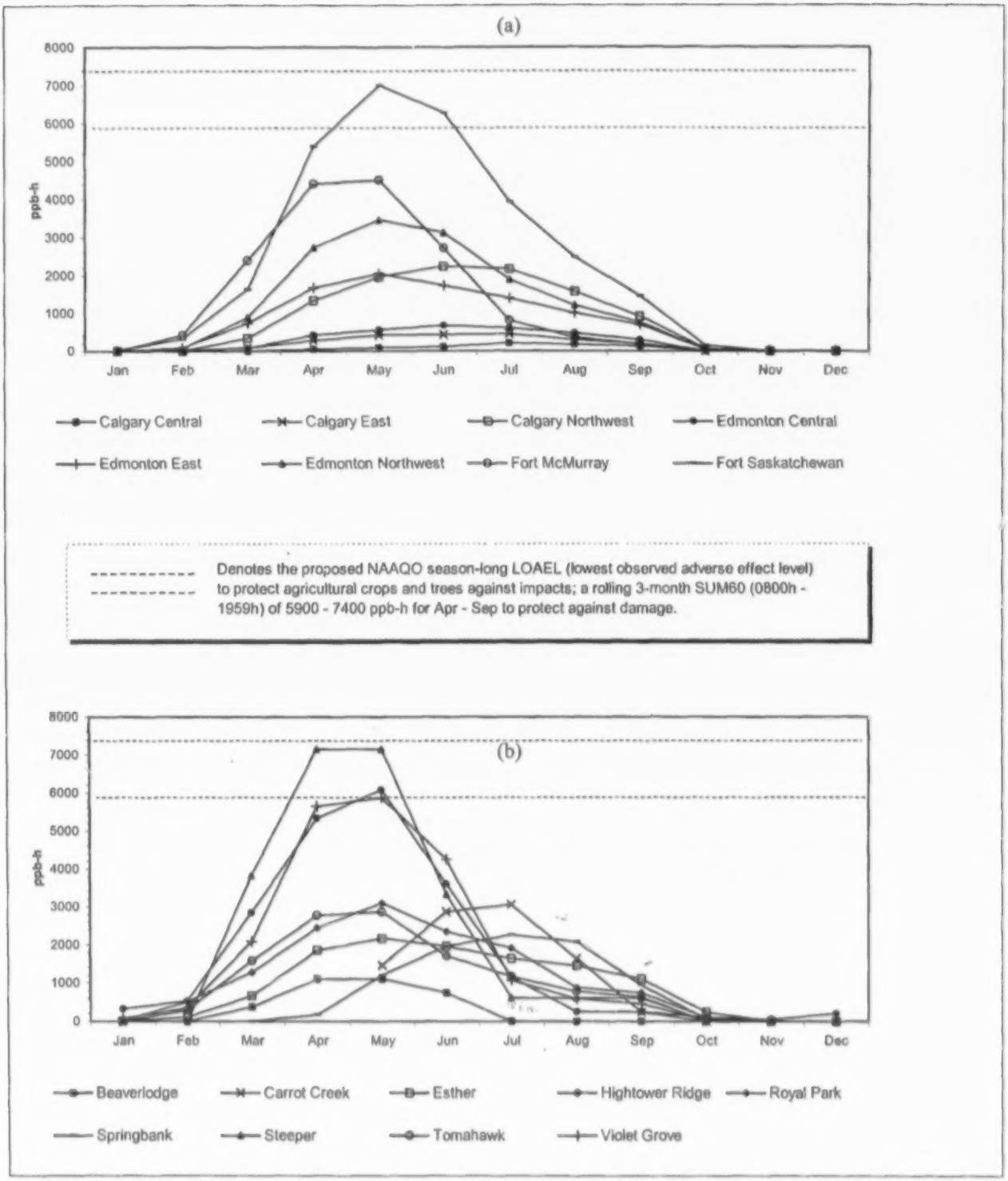

Figure 7.2 Average seasonal (3-month) SUM60 values in Alberta (1986–1998)

(a) urban stations, (b) rural stations

Table 7.2 Comparison of SUM60 values in Alberta and proposed NAAQO

Station	SUM60 range (5900–7400 ppb-h) exceed's	within	below	Years with these values
Beaverlodge			4	all available
Calgary Central			4	all available
Calgary East			4	all available
Calgary Northwest		4		87
Carrot Creek			4	all available
Edmonton Central			4	all available
Edmonton East		4		87, 98
	4			87
Edmonton Northwest		4		87, 91, 97, 98
	4			87, 91, 97
Esther		4		98
Fort McMurray	4			89, 90
Fort Saskatchewan		4		88, 91
	4			87, 88, 91, 94, 95
Hightower Ridge		4		97, 98
	4			97
Royal Park		4		97
Springbank			4	all available
Steeper		4		98
Tomahawk			4	all available
Violet Grove	4			98

Note: Years not listed had SUM60 values below the NAAQO range.

8.0 CONCLUSIONS

In Alberta, most ozone episodes (periods when ozone concentrations are elevated) occur in the months of May–August during periods of high temperature and radiation, low wind speeds, and low NO concentrations. Rural stations tend to have higher average ozone concentrations and urban stations have higher maximums and more exceedances of the 1-hour guideline. Most stations have a slight ozone–wind speed dependence; however, low winds speed is required for maximum ozone concentrations. Few stations have ozone–wind direction dependence; however, 90-180° winds are occasionally accompanied by higher ozone concentrations. Average ozone concentration increases with increasing ambient temperature and with increasing wind speeds. High average ozone concentration (i.e., in rural areas) seems to be mainly a result of upper tropospheric ozone, whereas discrete maximums (in urban areas and/or industrial areas) can be attributed to photochemistry

There is little concern about achieving the current AAAQG for 1-hour ozone concentration (82 ppb) at most stations. Urban areas tend to act as ozone sinks as a result of high concentrations of NO, which reacts with ozone to form NO_2. Fort Saskatchewan is the only urban station that has some difficulty meeting the 1-hour guideline. Violet Grove, which had 11 exceedances of the 1-hour ozone guideline in three years (1996–1998), is one rural station that has difficulty meeting the guideline.

Elevated ozone concentrations in rural Alberta are often measured during conditions that are unfavourable to photochemical ozone production, and ozone episodes often occur in the spring or even fall and winter. This implies that high rural ozone levels are natural and could not be reduced by regulating anthropogenic emissions. Transport of ozone from the upper troposphere and possibly stratospheric intrusion play a part in the relatively high ozone concentrations in Alberta's rural areas. The high natural or background ozone levels in rural Alberta may also be enhanced by photochemistry when precursors are transported from urban areas.

Generally, 8-hour averaged ozone concentrations are low in Alberta. The running 8-hour average acts to smooth out 1-hour values and get rid of noise. Average 8-hour concentrations are higher in rural areas, as were 1-hour concentrations, but the 8-hour maximums are similar in the rural and urban settings. Violet Grove and Fort Saskatchewan have the highest 8-hour ozone concentrations, as they do 1-hour concentrations. However, the rural stations—Steeper, Violet Grove, and Hightower Ridge—have the greatest percentages of 8-hour ozone concentrations at or above 65 ppb.

The proposed 8-hour CWS for ozone of 65 ppb was not exceeded in Alberta over the years investigated. High background ozone concentrations would make compliance difficult in rural areas; however, the proposed CWS applies only to stations with populations over 100 000 (Edmonton and Calgary). The Alberta stations that had 8-hour values greater than 65 ppb over the reference period were Fort Saskatchewan, Hightower Ridge, and Royal Park over 3-year averaging periods. However, none of these stations would have to comply with the CWS. Edmonton Northwest is the only urban station that may have difficulty complying, given that it had an 8-hour value of 67 ppb averaged over 1997–1998. Although this is a 2-year period, it is valid under the data completeness criteria for the proposed CWS. In terms of across-border

comparison to the United States, Alberta ozone values do not exceed the EPA 3-year, 8-hour ozone standard of 80 ppb, and Alberta rarely has discrete 8-hour concentrations above 80 ppb.

Of the vegetative indices investigated for Alberta, the SUM40 index had the greatest magnitudes in Alberta. This is because a large number of ozone observations in Alberta occur in the 40–50 ppb range. The highest SUM60 values were found in areas of industrial influence—Fort Saskatchewan and Fort McMurray. On average, the stations with the highest index values were Fort Saskatchewan, Hightower Ridge, and Steeper.

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Table AI.1 Percentile summary for 1-hour ozone concentrations at Alberta stations (ppb)

Station	Time Period	Mean	Percentiles										
			Min	1st	5th	10th	25th	50th	75th	90th	95th	98th	Max
Beaverlodge	01/Nov/97 - 31/Dec/98	28	0	1	8	12	19	29	37	42	46	51	76
Calgary Central	01/Jun/86 - 31/Dec/98	14	0	0	0	1	4	12	22	31	36	41	79
Calgary East	01/Jun/86 - 31/Dec/98	16	0	0	0	0	2	14	27	36	41	47	82
Calgary Northwest	01/Jun/86 - 31/Dec/98	23	0	0	1	3	10	22	33	43	48	54	106
Carrot Creek	01/May/98 - 31/Dec/98	25	0	0	1	3	11	24	38	47	51	56	77
Edmonton Central	01/Jul/86 - 31/Dec/98	16	0	1	2	3	6	14	24	34	39	46	93
Edmonton East	01/Jul/86 - 31/Dec/98	21	0	0	2	3	9	20	31	41	46	52	110
Edmonton Northwest	01/Jul/86 - 31/Dec/98	18	0	0	0	1	4	15	28	39	46	53	102
Esther	01/Jan/95 - 31/Dec/98	29	1	8	12	15	21	28	35	43	49	54	80
Fort McMurray	01/Jul/86 - 31/Dec/98	21	0	0	1	3	9	20	31	41	47	54	128
Fort Saskatchewan	01/Jul/86 - 31/Dec/98	23	0	0	1	2	10	23	35	45	51	58	116
Hightower Ridge	01/Jan/96 - 31/Dec/98	40	0	12	21	26	33	41	48	53	56	60	88
Royal Park	01/Jul/92 - 31/May/97	28	0	1	7	12	19	28	37	45	50	56	106
Springbank	23/Feb/94 - 30/Jun/96	27	0	1	5	9	17	28	37	44	48	53	86
Steeper	01/Dec/97 - 31/Dec/98	35	0	4	11	16	26	37	46	51	55	60	77
Tomahawk	29/Jan/97 - 3/Dec/98	29	0	1	7	10	18	29	39	47	52	56	74
Violet Grove	01/Jan/96 - 31/Dec/98	32	0	6	12	16	23	31	40	47	52	58	185

Table AI.1 Percentile summary for 1-hour ozone concentrations at Alberta stations (ppb)

Station	Time Period	Mean	Percentiles										
			Min	1st	5th	10th	25th	50th	75th	90th	95th	98th	Max
Beaverlodge	01/Nov/97 - 31/Dec/98	28	0	1	8	12	19	29	37	42	46	51	76
Calgary Central	01/Jun/86 - 31/Dec/98	14	0	0	0	1	4	12	22	31	36	41	79
Calgary East	01/Jun/86 - 31/Dec/98	16	0	0	0	0	2	14	27	36	41	47	82
Calgary Northwest	01/Jun/86 - 31/Dec/98	23	0	0	1	3	10	22	33	43	48	54	106
Carrot Creek	01/May/98 - 31/Dec/98	25	0	0	1	3	11	24	38	47	51	56	77
Edmonton Central	01/Jul/86 - 31/Dec/98	16	0	1	2	3	6	14	24	34	39	46	93
Edmonton East	01/Jul/86 - 31/Dec/98	21	0	0	2	3	9	20	31	41	46	52	110
Edmonton Northwest	01/Jul/86 - 31/Dec/98	18	0	0	0	1	4	15	28	39	46	53	102
Esther	01/Jan/95 - 31/Dec/98	29	1	8	12	15	21	28	35	43	49	54	80
Fort McMurray	01/Jul/86 - 31/Dec/98	21	0	0	1	3	9	20	31	41	47	54	128
Fort Saskatchewan	01/Jul/86 - 31/Dec/98	23	0	0	1	2	10	23	35	45	51	58	116
Hightower Ridge	01/Jan/96 - 31/Dec/98	40	0	12	21	26	33	41	48	53	56	60	88
Royal Park	01/Jul/92 - 31/May/97	28	0	1	7	12	19	28	37	45	50	56	106
Springbank	23/Feb/94 - 30/Jun/96	27	0	1	5	9	17	28	37	44	48	53	86
Steeper	01/Dec/97 - 31/Dec/98	35	0	4	11	16	26	37	46	51	55	60	77
Tomahawk	29/Jan/97 - 3/Dec/98	29	0	1	7	10	18	29	39	47	52	56	74
Violet Grove	01/Jan/96 - 31/Dec/98	32	0	6	12	16	23	31	40	47	52	58	185

Table AI.2 Percentile summary for 8-hour ozone concentrations at Alberta stations (ppb)

Station	Time Period	Mean	Percentiles										
			Min	1st	5th	10th	25th	50th	75th	90th	95th	98th	Max
Beaverlodge	01/Nov/97 - 31/Dec/98	28	0	4	9	13	20	29	36	41	44	49	62
Calgary Central	01/Jun/86 - 31/Dec/98	14	0	0	1	3	6	13	20	28	32	38	65
Calgary East	01/Jun/86 - 31/Dec/98	16	0	0	1	2	6	15	24	33	37	43	65
Calgary Northwest	01/Jun/86 - 31/Dec/98	23	0	1	4	6	13	22	31	40	45	50	81
Carrot Creek	01/May/98 - 31/Dec/98	25	0	0	4	7	13	24	35	43	48	53	63
Edmonton Central	01/Jul/86 - 31/Dec/98	16	0	1	3	4	8	15	23	31	37	42	75
Edmonton East	01/Jul/86 - 31/Dec/98	21	0	1	4	6	11	20	30	38	43	49	83
Edmonton Northwest	01/Jul/86 - 31/Dec/98	18	0	0	1	2	6	16	26	36	42	49	84
Esther	01/Jan/95 - 31/Dec/98	29	3	9	14	17	22	28	35	42	46	52	75
Fort McMurray	01/Jul/86 - 31/Dec/98	21	0	1	3	5	11	20	30	39	44	50	80
Fort Saskatchewan	01/Jul/86 - 31/Dec/98	23	0	0	2	5	12	23	33	43	48	55	86
Hightower Ridge	01/Jan/96 - 31/Dec/98	40	2	13	21	26	34	41	48	53	56	59	70
Royal Park	01/Jul/92 - 31/May/97	28	0	4	10	14	20	28	37	44	48	53	78
Springbank	23/Feb/94 - 30/Jun/96	27	0	3	8	12	19	27	35	42	46	50	71
Steeper	01/Dec/97 - 31/Dec/98	35	0	6	12	17	26	37	46	50	54	59	70
Tomahawk	29/Jan/97 - 3/Dec/98	29	0	3	8	11	19	29	38	45	50	54	68
Violet Grove	01/Jan/96 - 31/Dec/98	31	0	8	13	17	24	31	39	46	51	56	101

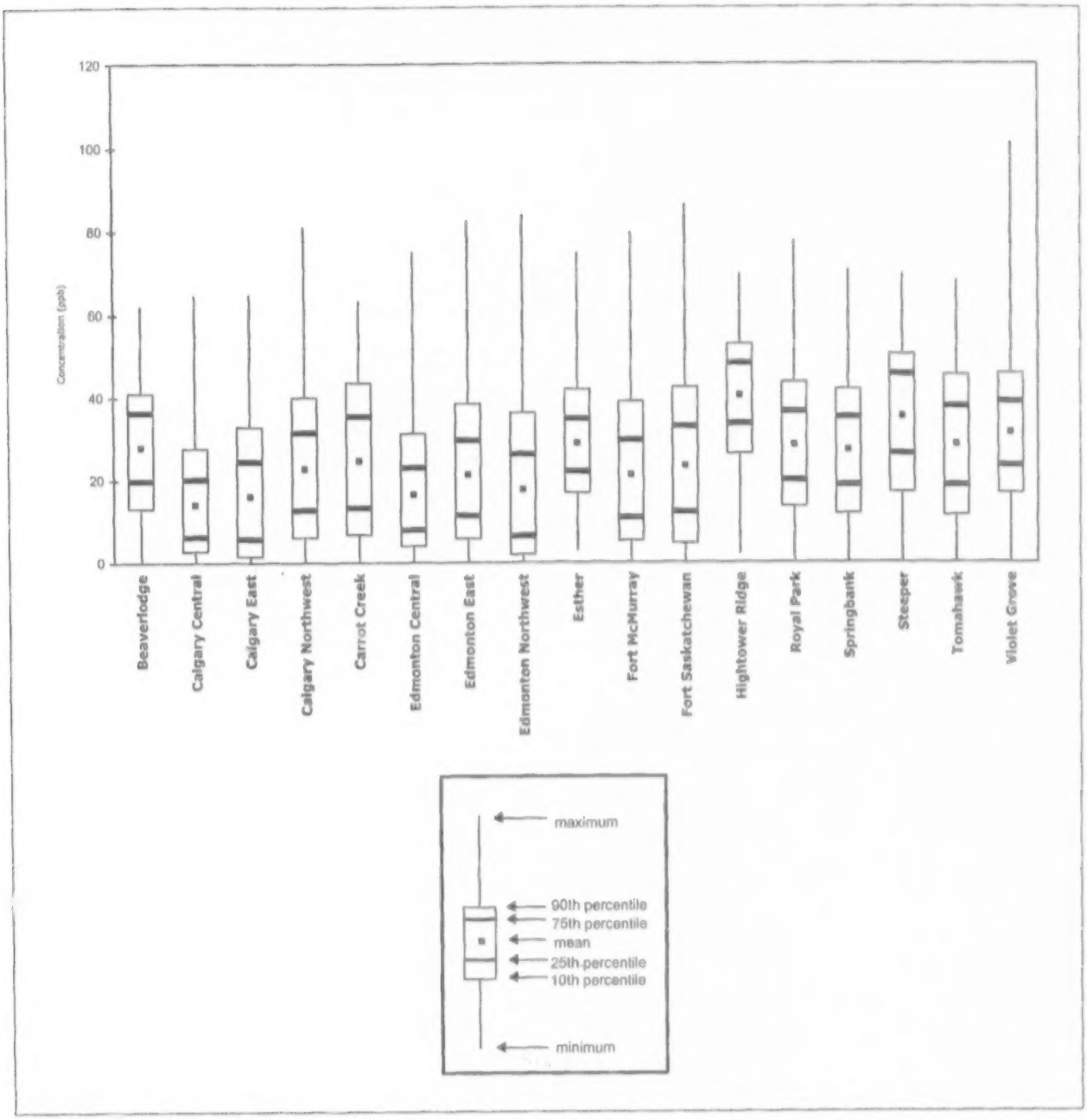


Figure AI.1 Average 8-hour ozone distribution in Alberta, 1986–1998

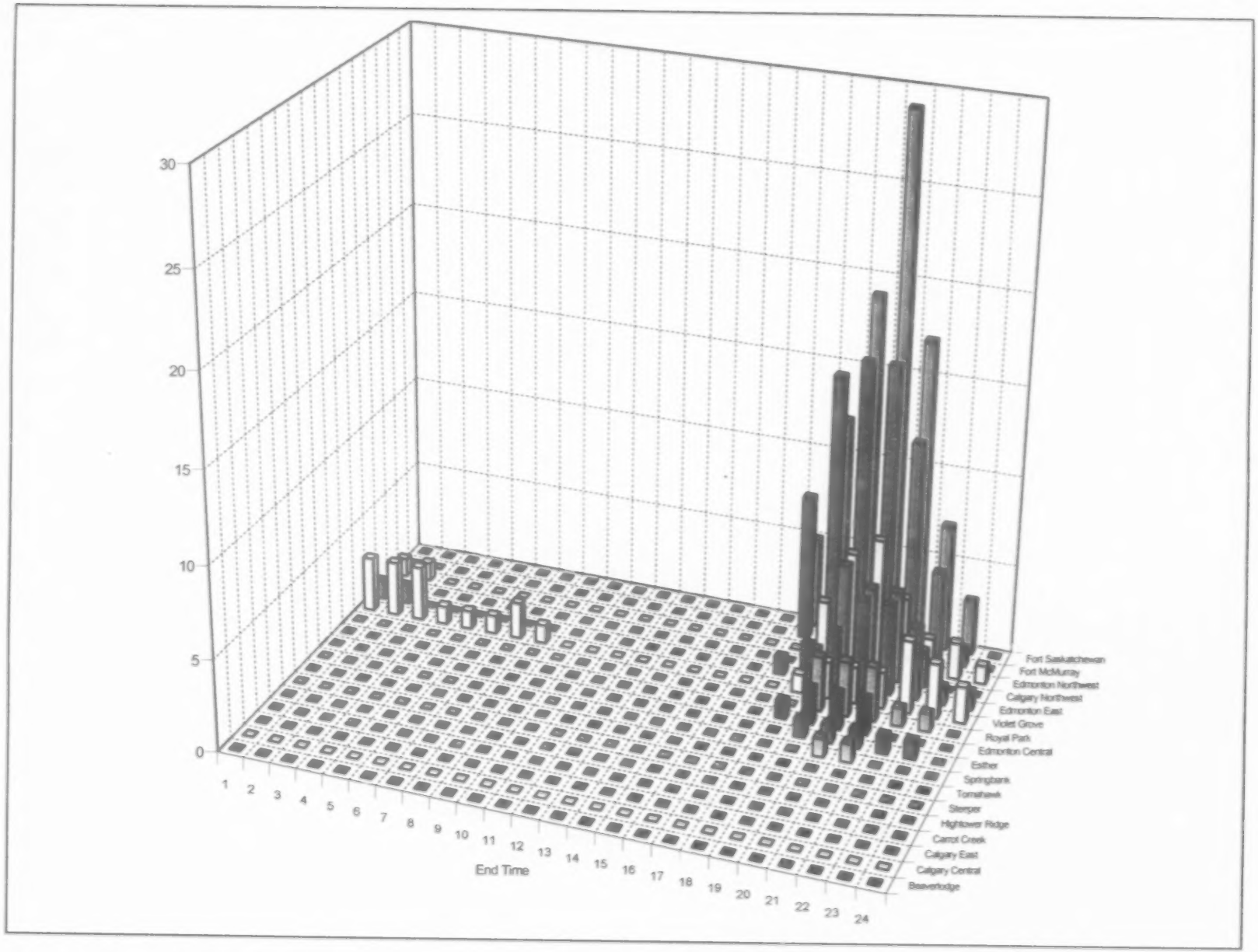


Figure AI.2 Site average count of 8-hour ozone >70 ppb by end time (1986–1998)

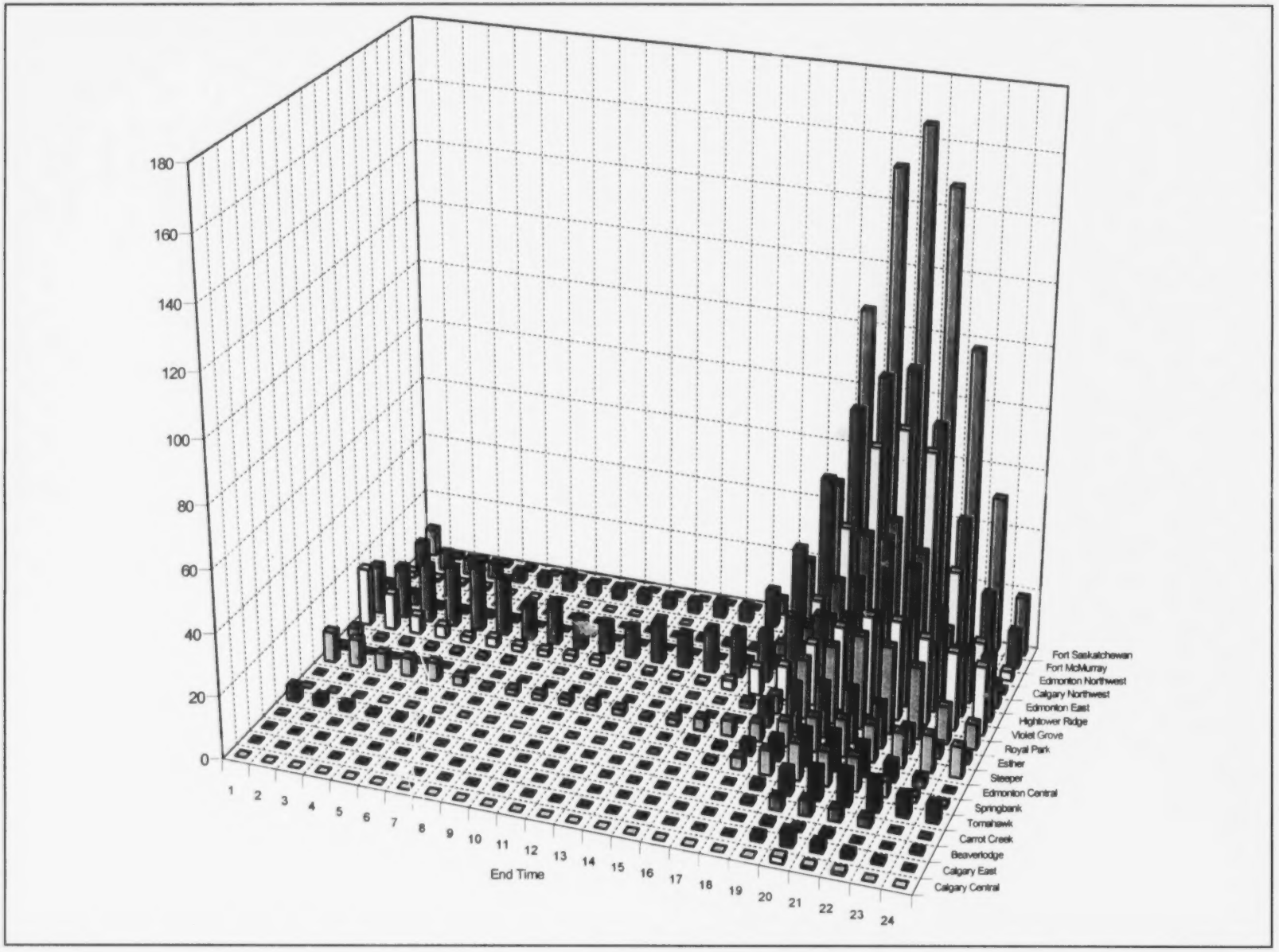


Figure AI.3 Site average count of 8-hour ozone >60 ppb by end time (1986–1998)

APPENDIX II WIND AND TEMPERATURE DATA

Table AII.1 Beaufort Scale of Wind Force

Beaufort number	*General description*	*Land and sea observations for estimating wind speeds*	*Wind speed 10 m above ground (km/h)*
0	Calm	Smoke rises vertically. Sea like mirror.	Less than 1
1	Light air	Smoke, but not wind vane, shows direction of wind. Slight ripples at sea	1 - 5
2	Light breeze	Wind felt on face, leaves rustle, wind vanes move. Small, short wavelets.	6 - 11
3	Gentle breeze	Leaves and small twigs moving constantly, small flags extended. Large wavelets, scattered whitecaps.	12 - 19
4	Moderate breeze	Dust and loose paper raised, small branches moved. Small waves, frequent whitecaps.	20 - 28
5	Fresh breeze	Small leafy trees swayed. Moderate waves.	29 - 38
6	Strong breeze	Large branches in motion, whistling heard in utility wires. Large waves, some spray.	39 - 49
7	Near gale	Whole trees in motion. White foam from breaking waves.	50 - 61
8	Gale	Twigs break off trees. Moderately high waves of great length.	62 - 74
9	Strong gale	Slight structural damage occurs. Crests of waves begin to roll over. Spray may impede visibility.	75 - 88
10	Storm	Trees uprooted, condsiderable structural damage. Sea white with foam, heavy tumbling of sea.	89 - 102
11	Violent Storm	Very rare; widespread damage. Unusually high waves.	103 - 118
12	Hurricane	Very rare; much foam and spray greatly reduce visibility.	119 and over

(Moran and Morgan, 1997)

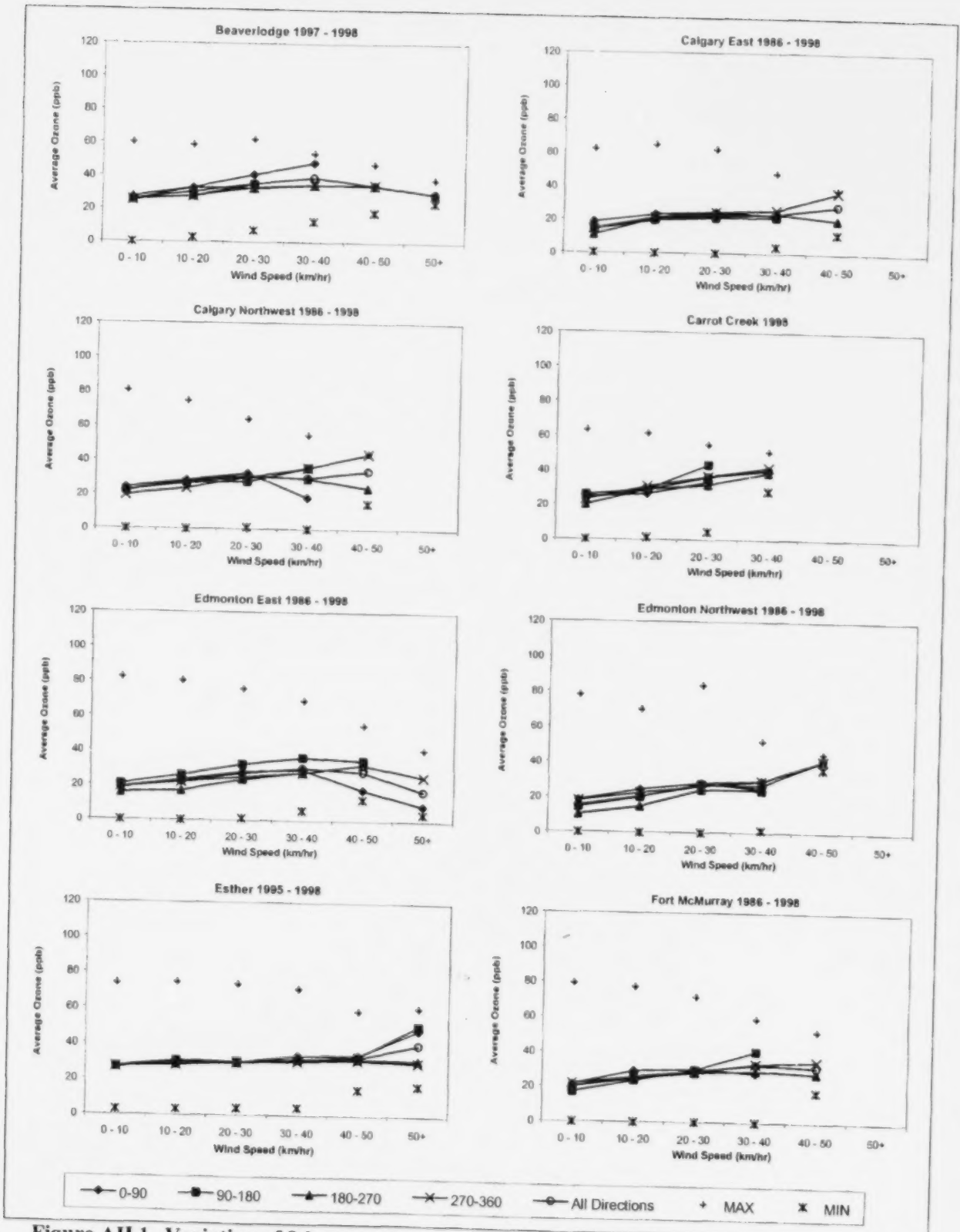


Figure AII.1 Variation of 8-hour ozone concentration with wind speed for different wind directions

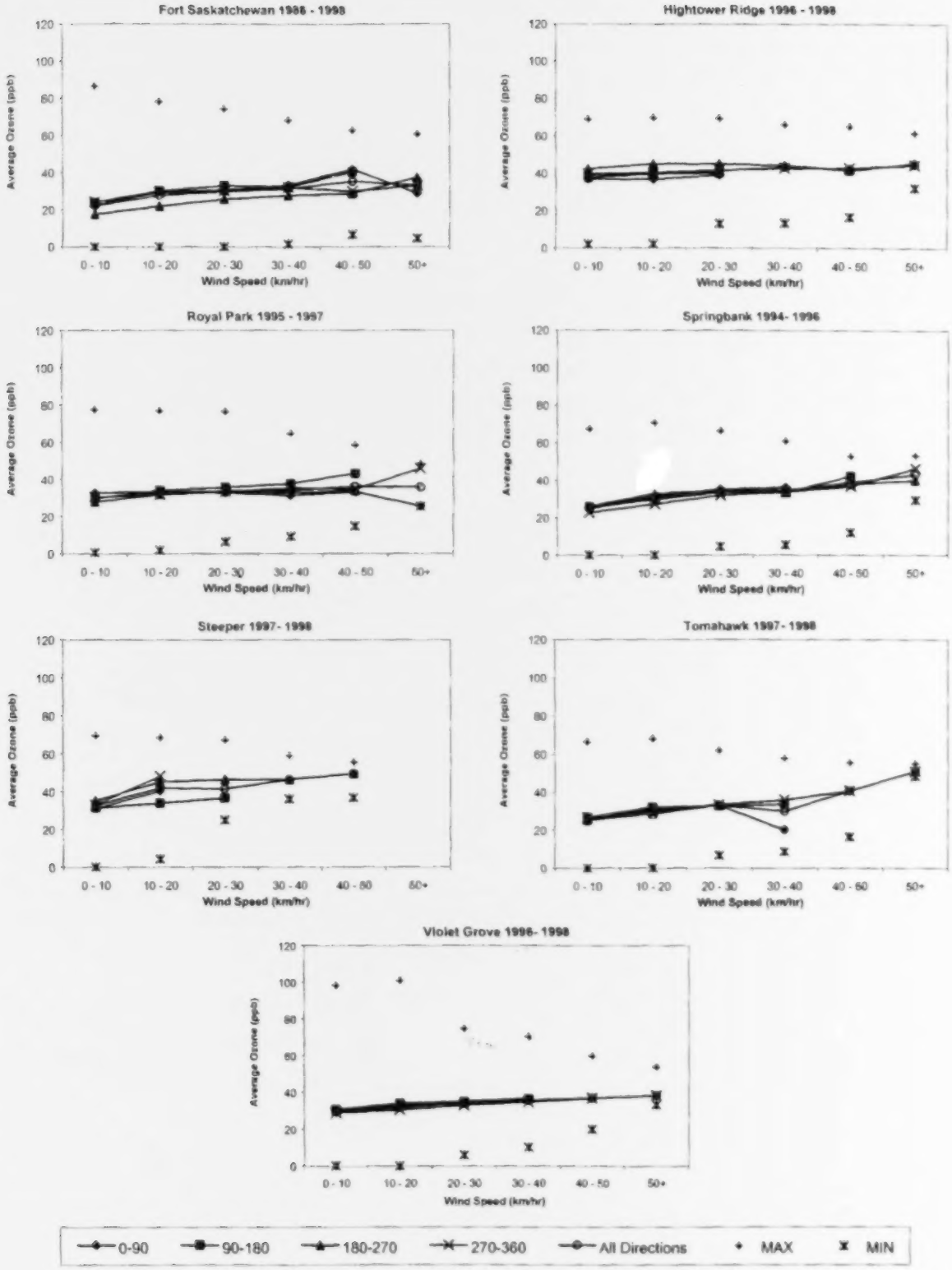


Figure AII.1 (continued)

Table AII.2 Range of 1-hour ozone values by wind speed

Beaverlodge (1997 - 1998)

WSP	Ozone (ppb)			
(km/hr)	MEAN	MAX	MIN	STDEV
0 - 10	25	71	0	11
10 - 20	32	62	0	10
20 - 30	38	76	6	9
30 - 40	39	49	19	5
40 - 50	36	51	22	6
50+	32	40	28	4

Calgary Northwest (1986 - 1998)

WSP	Ozone (ppb)			
(km/hr)	MEAN	MAX	MIN	STDEV
0 - 10	21	106	0	15
10 - 20	32	82	0	12
20 - 30	38	68	3	9
30 - 40	41	59	14	9
40 - 50	43	47	30	6
50+				

Edmonton East (1986 - 1998)

WSP	Ozone (ppb)			
(km/hr)	MEAN	MAX	MIN	STDEV
0 - 10	17	96	0	14
10 - 20	23	96	0	14
20 - 30	28	110	0	13
30 - 40	32	96	0	12
40 - 50	35	59	0	17
50+	16	32	4	8

Esther (1995 - 1998)

WSP	Ozone (ppb)			
(km/hr)	MEAN	MAX	MIN	STDEV
0 - 10	25	73	1	10
10 - 20	30	79	1	11
20 - 30	32	80	3	10
30 - 40	34	80	4	9
40 - 50	35	62	12	8
50+	44	62	16	13

Fort Saskatchewan (1986 - 1998)

WSP	Ozone (ppb)			
(km/hr)	MEAN	MAX	MIN	STDEV
0 - 10	21	116	0	15
10 - 20	32	92	0	14
20 - 30	35	74	0	13
30 - 40	37	72	0	13
40 - 50	43	68	12	12
50+	37	66	22	8

Royal Park (1995 - 1997)

WSP	Ozone (ppb)			
(km/hr)	MEAN	MAX	MIN	STDEV
0 - 10	29	76	0	14
10 - 20	33	78	1	12
20 - 30	36	106	4	11
30 - 40	39	95	9	11
40 - 50	40	57	10	9
50+	39	52	29	10

Steeper (1997 - 1998)

WSP	Ozone (ppb)			
(km/hr)	MEAN	MAX	MIN	STDEV
0 - 10	33	71	0	14
10 - 20	42	77	10	10
20 - 30	43	70	27	7
30 - 40	47	62	35	7
40 - 50	51	55	36	6
50+				

Violet Grove (1996 - 1998)

WSP	Ozone (ppb)			
(km/hr)	MEAN	MAX	MIN	STDEV
0 - 10	29	86	0	12
10 - 20	33	161	0	12
20 - 30	37	185	0	12
30 - 40	39	132	10	12
40 - 50	39	65	20	10
50+	38	60	30	7

Calgary East (1986 - 1998)

WSP	Ozone (ppb)			
(km/hr)	MEAN	MAX	MIN	STDEV
0 - 10	13	82	0	13
10 - 20	26	72	0	11
20 - 30	31	68	2	9
30 - 40	34	60	8	10
40 - 50	36	39	29	3
50+				

Carrot Creek (1998)

WSP	Ozone (ppb)			
(km/hr)	MEAN	MAX	MIN	STDEV
0 - 10	22	77	0	15
10 - 20	35	71	2	13
20 - 30	43	59	18	8
30 - 40	47	55	31	6
40 - 50				
50+				

Edmonton Northwest (1986 - 1998)

WSP	Ozone (ppb)			
(km/hr)	MEAN	MAX	MIN	STDEV
0 - 10	12	93	0	14
10 - 20	24	102	0	14
20 - 30	32	90	0	12
30 - 40	34	59	8	11
40 - 50	44	47	40	3
50+				

Fort McMurray (1986 - 1998)

WSP	Ozone (ppb)			
(km/hr)	MEAN	MAX	MIN	STDEV
0 - 10	19	91	0	14
10 - 20	31	128	0	13
20 - 30	35	76	0	12
30 - 40	38	66	0	11
40 - 50	38	53	29	8
50+				

Hightower Ridge (1996 - 1998)

WSP	Ozone (ppb)			
(km/hr)	MEAN	MAX	MIN	STDEV
0 - 10	39	88	2	12
10 - 20	40	88	2	11
20 - 30	42	73	0	9
30 - 40	44	73	13	9
40 - 50	42	64	12	8
50+	43	59	32	8

Springbank (1994 - 1996)

WSP	Ozone (ppb)			
(km/hr)	MEAN	MAX	MIN	STDEV
0 - 10	23	75	0	13
10 - 20	32	86	0	12
20 - 30	38	68	11	9
30 - 40	41	63	15	7
40 - 50	46	62	15	9
50+	46	52	39	4

Tomahawk (1997 - 1998)

WSP	Ozone (ppb)			
(km/hr)	MEAN	MAX	MIN	STDEV
0 - 10	25	73	0	14
10 - 20	31	74	0	13
20 - 30	36	67	5	11
30 - 40	32	55	11	11
40 - 50	46	56	39	6
50+	56	57	55	1

Table AII.3 Range of 8-hour ozone values by wind speed

Beaverlodge (1997 - 1998)

WSP	Ozone (ppb)			
(km/hr)	MEAN	MAX	MIN	STDEV
0 - 10	26	60	0	11
10 - 20	30	59	3	10
20 - 30	35	62	7	9
30 - 40	39	54	13	7
40 - 50	35	47	18	6
50+	30	38	24	5

Calgary East (1986 - 1998)

WSP	Ozone (ppb)			
(km/hr)	MEAN	MAX	MIN	STDEV
0 - 10	15	62	0	11
10 - 20	21	65	0	11
20 - 30	23	62	0	11
30 - 40	24	48	4	10
40 - 50	29	38	12	8
50+				

Calgary Northwest (1986 - 1998)

WSP	Ozone (ppb)			
(km/hr)	MEAN	MAX	MIN	STDEV
0 - 10	22	81	0	13
10 - 20	27	75	0	12
20 - 30	30	64	1	11
30 - 40	30	55	0	11
40 - 50	34	44	15	11
50+				

Carrot Creek (1998)

WSP	Ozone (ppb)			
(km/hr)	MEAN	MAX	MIN	STDEV
0 - 10	23	63	0	14
10 - 20	29	62	1	13
20 - 30	36	55	5	11
30 - 40	40	51	28	6
40 - 50				
50+				

Edmonton East (1986 - 1998)

WSP	Ozone (ppb)			
(km/hr)	MEAN	MAX	MIN	STDEV
0 - 10	19	83	0	12
10 - 20	22	81	0	12
20 - 30	27	76	1	11
30 - 40	30	69	6	10
40 - 50	28	55	12	12
50+	17	41	4	12

Edmonton Northwest (1986 - 1998)

WSP	Ozone (ppb)			
(km/hr)	MEAN	MAX	MIN	STDEV
0 - 10	15	78	0	13
10 - 20	21	70	0	13
20 - 30	27	84	0	12
30 - 40	27	52	2	11
40 - 50	41	45	37	4
50+				

Esther (1995 - 1998)

WSP	Ozone (ppb)			
(km/hr)	MEAN	MAX	MIN	STDEV
0 - 10	27	74	3	10
10 - 20	29	75	3	10
20 - 30	30	74	4	9
30 - 40	32	71	5	8
40 - 50	33	59	15	8
50+	40	61	17	12

Fort McMurray (1986 - 1998)

WSP	Ozone (ppb)			
(km/hr)	MEAN	MAX	MIN	STDEV
0 - 10	20	80	0	13
10 - 20	26	78	0	12
20 - 30	29	72	0	11
30 - 40	33	59	0	11
40 - 50	32	52	18	9
50+				

Fort Saskatchewan (1986 - 1998)

WSP	Ozone (ppb)			
(km/hr)	MEAN	MAX	MIN	STDEV
0 - 10	22	86	0	14
10 - 20	28	78	0	13
20 - 30	30	74	0	13
30 - 40	31	68	1	13
40 - 50	35	63	7	12
50+	33	61	5	10

Hightower Ridge (1996 - 1998)

WSP	Ozone (ppb)			
(km/hr)	MEAN	MAX	MIN	STDEV
0 - 10	39	69	2	11
10 - 20	40	70	2	10
20 - 30	41	69	13	9
30 - 40	43	66	13	9
40 - 50	42	65	16	8
50+	45	61	32	9

Royal Park (1995 - 1997)

WSP	Ozone (ppb)			
(km/hr)	MEAN	MAX	MIN	STDEV
0 - 10	30	78	1	12
10 - 20	33	77	2	11
20 - 30	34	76	7	11
30 - 40	34	65	9	10
40 - 50	36	59	15	8
50+	36	49	26	11

Springbank (1994 - 1996)

WSP	Ozone (ppb)			
(km/hr)	MEAN	MAX	MIN	STDEV
0 - 10	25	67	0	11
10 - 20	30	71	0	11
20 - 30	34	67	5	9
30 - 40	34	61	5	9
40 - 50	39	53	12	10
50+	43	53	29	8

Steeper (1997 - 1998)

WSP	Ozone (ppb)			
(km/hr)	MEAN	MAX	MIN	STDEV
0 - 10	33	70	0	13
10 - 20	42	68	4	10
20 - 30	42	67	25	7
30 - 40	47	59	36	6
40 - 50	50	56	37	7
50+				

Tomahawk (1997 - 1998)

WSP	Ozone (ppb)			
(km/hr)	MEAN	MAX	MIN	STDEV
0 - 10	26	66	0	13
10 - 20	31	68	0	13
20 - 30	33	62	7	11
30 - 40	30	58	8	11
40 - 50	41	55	16	8
50+	51	55	48	4

Violet Grove (1996 - 1998)

WSP	Ozone (ppb)			
(km/hr)	MEAN	MAX	MIN	STDEV
0 - 10	30	98	0	12
10 - 20	32	101	0	11
20 - 30	34	75	6	10
30 - 40	36	70	10	11
40 - 50	37	60	20	10
50+	38	54	33	6

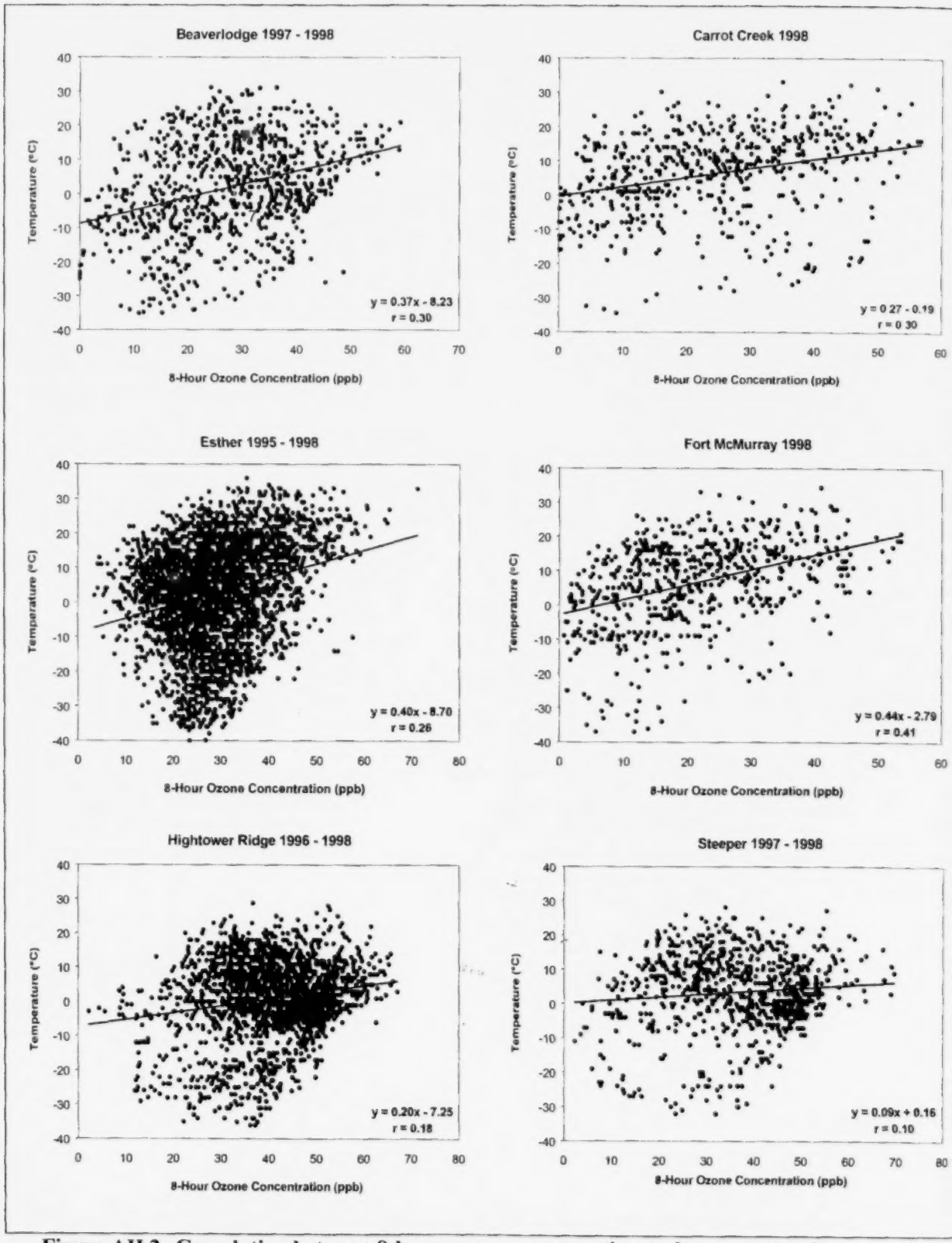
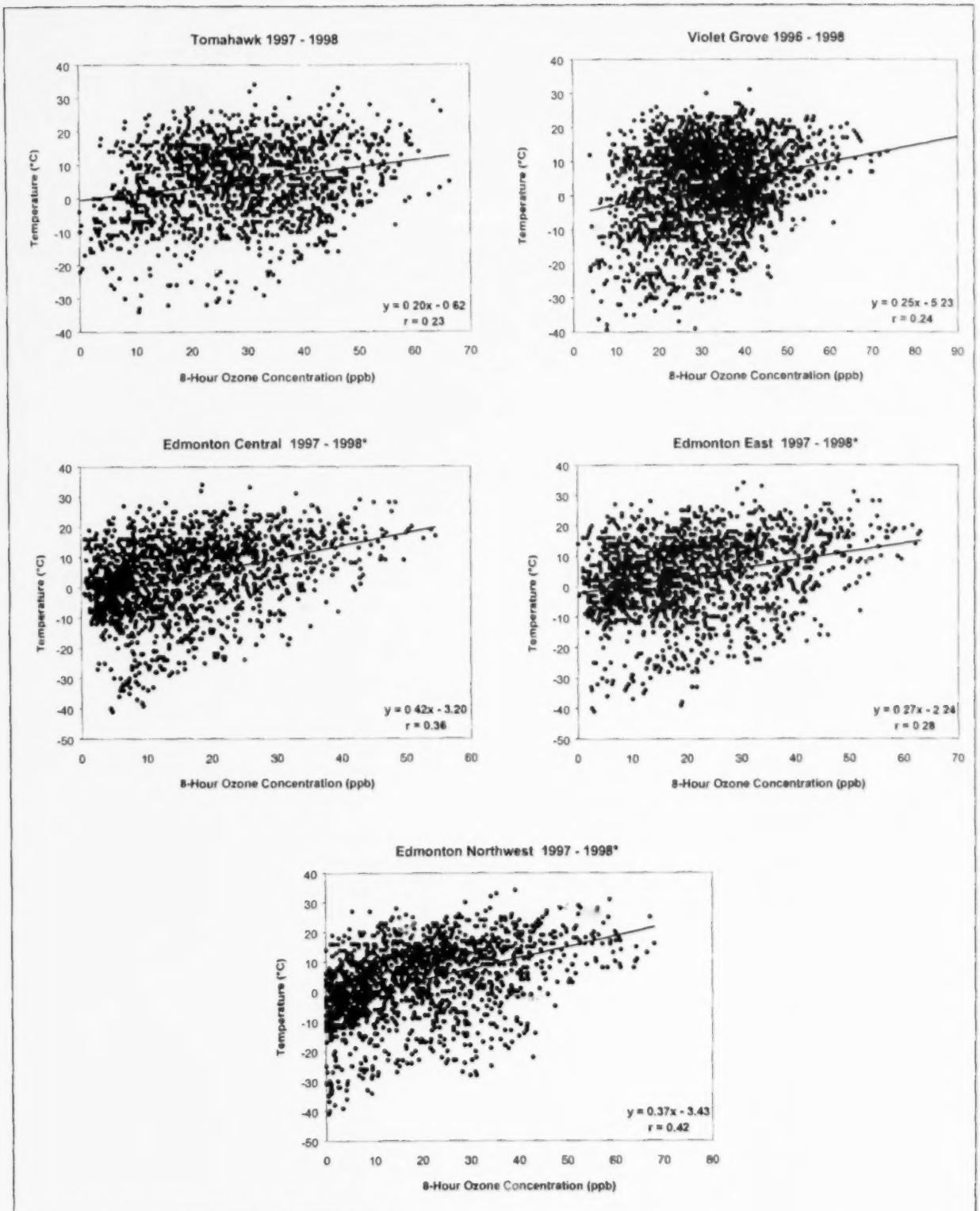


Figure AII.2 Correlation between 8-hour ozone concentration and temperature in Alberta



* Temperature data used from Tomahawk 1997 - 1998

Figure AII.2 (continued)

APPENDIX III VEGETATIVE INDICES

Table AIII.1 Average seasonal (3-month) SUM40 values in Alberta

Station	Dates (dd/mm/yr)	Seasonal SUM40 (mb-h)											
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Beaverlodge	01/11/97 - 31/12//98	4382	7609	17783	25262	23349	14031	9129	8312	7811	3412	1458	2269
Calgary Central	01/06/86 - 31/12/98	0	129	1344	4296	6296	6489	5224	3368	1713	254	3	0
Calgary East	01/06/86 - 31/12/98	219	1846	6631	12294	14273	11246	8400	5675	3663	1167	325	88
Calgary Northwest	01/06/86 - 31/12/98	1561	6465	16139	25288	28523	24368	20928	15043	9300	3374	1054	560
Carrot Creek	01/05/98 - 31/12/98					18790	29438	24983	22025	12196	5282	5021	4201
Edmonton Central	01/07/86 - 31/12/98	41	664	3662	8944	11204	10385	6902	4564	2512	361	38	6
Edmonton East	01/07/86 - 31/12/98	511	4659	12519	21593	22865	18493	12176	8414	5180	1578	338	172
Edmonton Northwest	01/07/86 - 31/12/98	516	3245	10142	19810	22986	20143	12923	8208	4415	1041	311	245
Esther	01/01/95 - 31/12/98	1333	7408	15237	25612	28577	26965	23062	17857	11778	4279	445	307
Fort McMurray	01/07/86 - 31/12/98	1716	7247	17298	26595	25621	17093	7957	4480	2939	1073	713	583
Fort Saskatchewan	01/07/86 - 31/12/98	3138	10517	20257	31945	33097	26631	18214	13091	8757	3886	1574	1355
Hightower Ridge	01/01/96 - 31/12/98	32208	30840	41626	43518	40404	28175	21091	15801	15872	19498	29271	30642
Royal Park	01/07/92 - 31/05/97	7385	17280	24950	32305	27845	22559	13533	10612	8327	4577	2139	2332
Springbank	23/02/94 - 30/06/96	2097	10241	19487	27439	27751	21894	18766	14203	8828	3441	616	282
Steeper	01/12/97 - 31/12/98	26299	20091	28745	30812	34470	20970	12859	11758	10921	8374	12025	17708
Tomahawk	29/01/97 - 03/12/98	6489	14027	26218	33310	29846	21650	15184	12642	8811	4033	2501	2336
Violet Grove	01/01/96 - 31/12/98	9851	15778	26171	32235	29410	22322	14910	11624	8931	5655	5840	5228

Table AIII.2 Average seasonal (3-month) SUM50 values in Alberta

Station	Dates (dd/mm/yr)	Seasonal SUM50 (ppb-h)											
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Beaverlodge	01/11/97 - 31/12//98	369	52	3458	7470	9197	5894	1985	359	256	153	185	185
Calgary Central	01/06/86 - 31/12/98	0	4	93	624	981	1169	1180	855	525	24	0	0
Calgary East	01/06/86 - 31/12/98	0	101	1229	2858	3642	2842	2094	1309	835	80	8	0
Calgary Northwest	01/06/86 - 31/12/98	0	694	4516	10131	12819	11128	8577	5567	3116	483	20	0
Carrot Creek	01/05/98 - 31/12/98					8430	13202	9803	7381	2660	756	354	303
Edmonton Central	01/07/86 - 31/12/98	0	123	716	2603	3175	3148	2016	1391	860	24	8	0
Edmonton East	01/07/86 - 31/12/98	22	641	3382	7690	9127	7457	4651	3019	1997	297	30	14
Edmonton Northwest	01/07/86 - 31/12/98	30	726	3905	9417	11165	9740	5616	3506	1875	180	34	24
Esther	01/01/95 - 31/12/98	0	966	3500	8824	11576	10465	8621	6235	4826	1345	13	0
Fort McMurray	01/07/86 - 31/12/98	107	1667	6787	11795	11967	7474	2755	1301	685	78	33	0
Fort Saskatchewan	01/07/86 - 31/12/98	576	3189	8216	17068	19148	15603	9386	6053	3439	809	79	281
Hightower Ridge	01/01/96 - 31/12/98	11743	15290	24681	28116	25640	14457	7126	3744	3426	4190	6502	8611
Royal Park	01/07/92 - 31/05/97	375	4347	8451	14325	13464	10158	5440	3148	2702	997	179	0
Springbank	23/02/94 - 30/06/96	0	1071	3518	7248	9516	8520	6701	5262	3084	536	0	0
Steeper	01/12/97 - 31/12/98	6149	6149	16121	21490	22651	11017	2967	1958	2480	873	722	1862
Tomahawk	29/01/97 - 03/12/98	712	3935	10259	16811	16102	11088	6111	4069	2710	473	0	50
Violet Grove	01/01/96 - 31/12/98	1364	4387	10394	16625	15613	10714	5564	3653	2563	581	481	463

APPENDIX III VEGETATIVE INDICES

Table AIII.1 Average seasonal (3-month) SUM40 values in Alberta

Station	Dates (dd/mm/yr)	Seasonal SUM40 (mb-h)											
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Beaverlodge	01/11/97 - 31/12//98	4382	7609	17783	25262	23349	14031	9129	8312	7811	3412	1458	2269
Calgary Central	01/06/86 - 31/12/98	0	129	1344	4296	6296	6489	5224	3368	1713	254	3	0
Calgary East	01/06/86 - 31/12/98	219	1846	6631	12294	14273	11246	8400	5675	3663	1167	325	88
Calgary Northwest	01/06/86 - 31/12/98	1561	6465	16139	25288	28523	24368	20928	15043	9300	3374	1054	560
Carrot Creek	01/05/98 - 31/12/98					18790	29438	24983	22025	12196	5282	5021	4201
Edmonton Central	01/07/86 - 31/12/98	41	664	3662	8944	11204	10385	6902	4564	2512	361	38	6
Edmonton East	01/07/86 - 31/12/98	511	4659	12519	21593	22865	18493	12176	8414	5180	1578	338	172
Edmonton Northwest	01/07/86 - 31/12/98	516	3245	10142	19810	22986	20143	12923	8208	4415	1041	311	245
Esther	01/01/95 - 31/12/98	1333	7408	15237	25612	28577	26965	23062	17857	11778	4279	445	307
Fort McMurray	01/07/86 - 31/12/98	1716	7247	17298	26595	25621	17093	7957	4480	2939	1073	713	583
Fort Saskatchewan	01/07/86 - 31/12/98	3138	10517	20257	31945	33097	26631	18214	13091	8757	3886	1574	1355
Hightower Ridge	01/01/96 - 31/12/98	32208	30840	41626	43518	40404	28175	21091	15801	15872	19498	29271	30642
Royal Park	01/07/92 - 31/05/97	7385	17280	24950	32305	27845	22559	13533	10612	8327	4577	2139	2332
Springbank	23/02/94 - 30/06/96	2097	10241	19487	27439	27751	21894	18766	14203	8828	3441	616	282
Steeper	01/12/97 - 31/12/98	26299	20091	28745	30812	34470	20970	12859	11758	10921	8374	12025	17708
Tomahawk	29/01/97 - 03/12/98	6489	14027	26218	33310	29846	21650	15184	12642	8811	4033	2501	2336
Violet Grove	01/01/96 - 31/12/98	9851	15778	26171	32235	29410	22322	14910	11624	8931	5655	5840	5228

Table AIII.2 Average seasonal (3-month) SUM50 values in Alberta

Station	Dates (dd/mm/yr)	Seasonal SUM50 (ppb-h)											
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Beaverlodge	01/11/97 - 31/12//98	369	52	3458	7470	9197	5894	1985	359	256	153	185	185
Calgary Central	01/06/86 - 31/12/98	0	4	93	624	981	1169	1180	855	525	24	0	0
Calgary East	01/06/86 - 31/12/98	0	101	1229	2858	3642	2842	2094	1309	835	80	8	0
Calgary Northwest	01/06/86 - 31/12/98	0	694	4516	10131	12819	11128	8577	5567	3116	483	20	0
Carrot Creek	01/05/98 - 31/12/98					8430	13202	9803	7381	2660	756	354	303
Edmonton Central	01/07/86 - 31/12/98	0	123	716	2603	3175	3148	2016	1391	860	24	8	0
Edmonton East	01/07/86 - 31/12/98	22	641	3382	7690	9127	7457	4651	3019	1997	297	30	14
Edmonton Northwest	01/07/86 - 31/12/98	30	726	3905	9417	11165	9740	5616	3506	1875	180	34	24
Esther	01/01/95 - 31/12/98	0	966	3500	8824	11576	10465	8621	6235	4826	1345	13	0
Fort McMurray	01/07/86 - 31/12/98	107	1667	6787	11795	11967	7474	2755	1301	685	78	33	0
Fort Saskatchewan	01/07/86 - 31/12/98	576	3189	8216	17068	19148	15603	9386	6053	3439	809	79	281
Hightower Ridge	01/01/96 - 31/12/98	11743	15290	24681	28116	25640	14457	7126	3744	3426	4190	6502	8611
Royal Park	01/07/92 - 31/05/97	375	4347	8451	14325	13464	10158	5440	3148	2702	997	179	0
Springbank	23/02/94 - 30/06/96	0	1071	3518	7248	9516	8520	6701	5262	3084	536	0	0
Steeper	01/12/97 - 31/12/98	6149	6149	16121	21490	22651	11017	2967	1958	2480	873	722	1862
Tomahawk	29/01/97 - 03/12/98	712	3935	10259	16811	16102	11088	6111	4069	2710	473	0	50
Violet Grove	01/01/96 - 31/12/98	1364	4387	10394	16625	15613	10714	5564	3653	2563	581	481	463

Table AIII.3 Average seasonal (3-month) SUM60 values in Alberta

Station	Dates (dd/mm/yr)	Seasonal SUM60 (ppb-h)											
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Beaverlodge	01/11/97 - 31/12//98	0	0	370	1116	1116	746	0	0	0	0	0	0
Calgary Central	01/06/86 - 31/12/98	0	0	5	46	84	107	202	166	132	0	0	0
Calgary East	01/06/86 - 31/12/98	0	16	86	284	420	437	449	304	195	0	0	0
Calgary Northwest	01/06/86 - 31/12/98	0	0	336	1325	1954	2235	2165	1571	917	74	0	0
Carrot Creek	01/05/98 - 31/12/98					1473	2876	3059	1646	243	0	0	0
Edmonton Central	01/07/86 - 31/12/98	0	20	73	426	556	681	608	469	304	0	0	0
Edmonton East	01/07/86 - 31/12/98	0	89	734	1672	2039	1722	1395	1008	700	48	14	14
Edmonton Northwest	01/07/86 - 31/12/98	0	57	878	2734	3454	3129	1891	1214	761	50	10	0
Esther	01/01/95 - 31/12/98	0	107	659	1854	2172	1967	1639	1457	1110	243	0	0
Fort McMurray	01/07/86 - 31/12/98	0	428	2394	4412	4505	2714	806	363	182	19	10	0
Fort Saskatchewan	01/07/86 - 31/12/98	22	322	1634	5391	6999	6282	3945	2479	1465	159	0	9
Hightower Ridge	01/01/96 - 31/12/98	320	533	2848	5330	6083	3606	1158	253	253	108	47	210
Royal Park	01/07/92 - 31/05/97	25	503	1275	2448	3096	2352	1920	880	748	99	13	0
Springbank	23/02/94 - 30/06/96	0	0	0	167	1203	1967	2274	2083	937	62	0	0
Steeper	01/12/97 - 31/12/98	0	0	3829	7156	7156	3327	617	617	617	0	0	0
Tomahawk	29/01/97 - 03/12/98	0	287	1584	2770	2872	1713	1170	780	643	0	0	0
Violet Grove	01/01/96 - 31/12/98	73	345	2093	5646	5882	4259	1075	588	463	21	0	0

Table AIII.4 Average seasonal (3-month) SUM70 values in Alberta

Station	Dates (dd/mm/yr)	Seasonal SUM70 (ppb-h)											
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Beaverlodge	01/11/97 - 31/12//98	0	0	0	0	0	0	0	0	0	0	0	0
Calgary Central	01/06/86 - 31/12/98	0	0	0	0	6	11	51	46	40	0	0	0
Calgary East	01/06/86 - 31/12/98	0	0	0	12	37	51	86	63	46	0	0	0
Calgary Northwest	01/06/86 - 31/12/98	0	0	0	24	120	334	553	464	241	0	0	0
Carrot Creek	01/05/98 - 31/12/98					0	218	218	218	0	0	0	0
Edmonton Central	01/07/86 - 31/12/98	0	0	0	47	87	117	154	118	90	0	0	0
Edmonton East	01/07/86 - 31/12/98	0	0	155	185	271	210	362	282	196	0	0	0
Edmonton Northwest	01/07/86 - 31/12/98	0	0	151	466	610	609	498	365	227	0	0	0
Esther	01/01/95 - 31/12/98	0	0	0	0	36	36	296	313	313	53	0	0
Fort McMurray	01/07/86 - 31/12/98	0	115	552	1137	1172	795	226	94	19	0	0	0
Fort Saskatchewan	01/07/86 - 31/12/98	0	13	117	757	1281	1513	1495	1064	635	23	0	0
Hightower Ridge	01/01/96 - 31/12/98	77	50	50	144	144	144	0	47	47	47	27	27
Royal Park	01/07/92 - 31/05/97	0	0	72	304	320	184	328	312	253	0	0	0
Springbank	23/02/94 - 30/06/96	0	0	0	0	72	323	637	637	261	0	0	0
Steeper	01/12/97 - 31/12/98	0	0	209	571	571	362	0	0	0	0	0	0
Tomahawk	29/01/97 - 03/12/98	0	0	0	35	144	217	324	216	142	0	0	0
Violet Grove	01/01/96 - 31/12/98	29	29	101	749	799	727	137	87	87	0	0	0

Table AIII.5 Average seasonal (3-month) AOT40 values in Alberta

Station	Dates (dd/mm/yr)	Seasonal AOT40 (ppb-h)											
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Beaverlodge	01/11/97 - 31/12//98	296	636	2410	4233	4384	2711	1293	821	714	235	108	150
Calgary Central	01/06/86 - 31/12/98	0	6	98	429	667	735	653	433	243	20	0	0
Calgary East	01/06/86 - 31/12/98	6	141	759	1614	1992	1573	1136	697	435	79	17	1
Calgary Northwest	01/06/86 - 31/12/98	83	626	2314	4408	5335	4617	3751	2529	1449	331	55	28
Carrot Creek	01/05/98 - 31/12/98					3747	5753	4622	3669	1725	619	577	515
Edmonton Central	01/07/86 - 31/12/98	1	75	431	1309	1654	1613	1057	690	396	23	4	0
Edmonton East	01/07/86 - 31/12/98	33	517	1852	3712	4183	3409	2165	1421	890	162	26	11
Edmonton Northwest	01/07/86 - 31/12/98	42	381	1696	3910	4699	4136	2469	1516	817	113	25	19
Esther	01/01/95 - 31/12/98	54	779	1981	4132	5022	4678	3914	2896	2045	622	25	17
Fort McMurray	01/07/86 - 31/12/98	143	1010	3250	5399	5363	3386	1324	644	376	87	50	32
Fort Saskatchewan	01/07/86 - 31/12/98	372	1585	3631	6994	7786	6402	4040	2649	1580	463	123	163
Hightower Ridge	01/01/96 - 31/12/98	6440	6643	10239	11571	10799	6485	3737	2328	2311	2985	4963	5698
Royal Park	01/07/92 - 31/05/97	647	2513	4193	6288	5677	4396	2508	1622	1322	555	191	141
Springbank	23/02/94 - 30/06/96	94	1076	2441	3950	4504	3836	3208	2467	1401	322	16	2
Steeper	01/12/97 - 31/12/98	4281	3924	7535	9235	9793	5079	1952	1613	1612	729	867	1973
Tomahawk	29/01/97 - 03/12/98	737	2268	5008	7249	6690	4514	2755	2015	1388	387	155	219
Violet Grove	01/01/96 - 31/12/98	1105	2391	4926	7452	7011	4981	2559	1748	1255	533	499	487